A DECISION SUPPORT SYSTEM FOR MULTI-OBJECTIVE FOREST MANAGEMENT. A STUDY IN THE QUEEN ELIZABETH NATIONAL FOREST PARK IN SCOTLAND

by

Vasiliki Kazana, B.Sc. (Forestry)

Ph. D.

University of Edinburgh
Department of Forestry and Natural Resources

1989

To my family

DECLARATION

I declare that this thesis has been composed by myself from the results of my own work, except where acknowledged to the contrary. I also declare that the work herein presented has not been submitted for any degree other than that of Doctor of Philosophy in the University of Edinburgh.

ABSTRACT

This research work includes the design and development of a computer-based decision support system (FORM) for tactical planning and management in multiple-use forests, where non-marketable products and services also have to be accommodated over time. The system aims to help managers in their deciding on the allocation of forest resources, while simultaneously trying to satisfy over time the longer term multiple objectives within physical and operational constraints. The basic features of the system are: (i) it leaves the forest managers with full control of the decision making process; so that they can provide their own answers and solutions to forest resource allocation problems; and (ii) it fosters the forest managers' abilities by providing analytical support for exploring new alternatives (trade-offs).

FORM consists of four components. The first (intelligence), refers to problem formulation and includes identification of objectives, constraints, alternative regimes, habitat types and models with respect to the objectives. The second (design), uses the outputs of the first component in a technological forecast model and produces technical coefficients (input-output functions). The third component uses a multi-objective optimization procedure, which results iteratively in 'trade-off' outputs. The input-output functions and the 'trade-off' outputs can be presented in tabular and/or graphical form. The fourth component (implementation) includes the final resource allocation scheme adopted after examining trade-offs.

The multi-objective programming method, which is used in component three to optimize multiple benefits over time is interactive and depends on progressive statement of preference information by the decision maker. The procedure starts by sampling randomly the efficient set. The non-dominated value vector is computed according to the L_∞-norm. The same criterion (i.e. L_∞-norm) is used to identify the most dissimilar value vectors of the gradually reduced subsets of the efficient set at each iteration. The method converges fast to the final solution. Acceptable solutions can be obtained within a number of iterations equal to the number of objective functions.

The technical coefficients for the optimization model are produced by a forest system simulation model. The decision variables in the system represent different forest management regimes. These have been expressed as functions of time to capture the dynamics of the forest ecosystem. Prediction of timber yields is based on Forestry Commission's yield models and the inventory subcompartment data file. Prediction of recreation use of forest habitats is based on statistical models obtained from a survey carried out in the Queen Elizabeth Forest Park in 1986.

The model is applied in the Queen Elizabeth National Forest Park, which forms part of the Aberfoyle Forest District in Central Scotland.

ACKNOWLEDGEMENTS

I would like to express my thanks to all those who have helped me during the various stages of this work.

I thank my supervisors Dr. W.E.S. Mutch and Mr R. Fawcett for helpful discussions and criticism during the preparation of this thesis. Mr R. Fawcett made available his single objective linear programming source code for the development of the model under investigation and I am grateful to him for this.

I would like to thank Dr. D.C. Malcolm, head of the Department of Forestry and Natural Resources and Dr. R.I. Muetzefeldt, Dr. C. Legg, Dr. J. Blyth, Dr. I. Taylor and Dr. J. Grace, members of staff, for helpful advice. I would also like to thank Mr. D. Haswell, Mr. J. Landless and Mrs M. Jackson, technical staff of the Department of Forestry & N.R., the staff of the Biological Support Team at EUCC and Dr. J. Glen from the Department of Business Studies for helpful discussions in the beginning of this project. I am indebted to Mrs. J. Ritchie for her hospitality and friendly assistance.

I would like to extend my appreciation to my colleagues, C. Ramdass, S. Harper, N. Schrimpton, F. Sinclair, A. Brenner, M. Wright, M. Richards, B. Maisels and T. Lehto, as well as my friends in Edinburgh, for giving me moral support at various stages of this work.

I am grateful to the Forestry Commission for permission to work in the Queen Elizabeth Forest Park and to Mr Roebuck, Mr. J. Baird and all the forestry staff of the Aberfoyle Forest District Office for their kindness and assistance.

I also wish to acknowledge the receipt of financial support from the Greek State Scholarships Foundation (I.K.Y.) and Schillizzi Foundation (England), without which the present work could not have been undertaken.

Finally, may I deeply thank my parents, my sister and Angelos for their support and tolerance from the beginning to the end.

CONTENTS

Page

NOTATION

- Throughout this thesis lower case boldface letters, such as **x**, **y** are used to denote vectors.
- Matrices are denoted by capital letters such as A, F, S.
- Superscripts such as $\mathbf{x}^1$ or $\mathbf{x}^2$ are used to refer to alternative value vectors.
- Subscripts such as $\mathbf{x}_1$ or $\mathbf{x}_2$ are used to refer to elements of a vector.
- The derivative of a function f(x) evaluated at $x = x_0$ is written

$$\partial f(x_0) / \partial x$$

Other mathematical symbols used in this thesis are:

$\in$: is an element of

$$\sum_{i=1}^{n} a_i = a_1 + a_2 + a_3 + \ldots + a_n$$

[a,b] is a closed interval. For example, $x \in [a,b]$ means $a \leq x \leq b$

$\subset$: is a subset of

$\|x\|$: is the norm of a vector. The length of a vector $\mathbf{x} = (x_1, x_2, \ldots, x_n)^T$ is $\sqrt{x_1^2 + x_2^2 + \ldots + x_n^2}$, where T means transpose.

$\exists$: a value exists

$\forall$: for any value

$\neq$: is different from

LIST OF FIGURES

Page

Page

Page

LIST OF TABLES

LIST OF APPENDICES

CHAPTER ONE. BACKGROUND TO THE PROBLEM

1.1 NATIONAL FORESTS. MULTI-OBJECTIVE PLANNING AND MANAGEMENT. DEALING WITH CONFLICT

In the last few decades foresters have faced an increasing demand for forest products and services. The main reasons for this are: more sophisticated needs of modern people, increase of income per capita, the environmental crisis, the technological revolution and greater political awareness.

Forests can no longer be seen solely as a source of timber. Recreation, wildlife conservation, water gathering and scenic beauty impose ever greater demands on forest lands. Especially in the national forests, forest planning and management become complex procedures. Forest managers try to solve problems of how to make the most of the limited available resources and decide on the extent to which different demands can be traded -off against each other.

The answer to such problems lies in the formulation of sound management systems which will help managers to arrive at better decisions. There is an apparent difficulty, however, in deciding what constitutes a sound management system. The needs of the modern society, which have led to the scarcity of natural resources do not allow a universally accepted definition.

The managers of the forest have to operate within a certain legal and political framework and within a given organizational regime to implement policy objectives. The frameworks vary greatly from country to country, making it impossible to formulate general principles which would guide the management of forest ecosystems. The services that forests can accommodate, apart from purely commercial timber production, have to be incorporated into management systems which are adjusted to the cultural needs of each society.

Stankey (1982), has distinguished two basic philosophies as polar ideals, which may define the range of management orientations that might be adopted with regard to wilderness: the anthropocentric philosophy and the biocentric philosophy, which stand diametrically opposed. My opinion is that these two attitudes can be generalized with regard to the management of any forest, where different uses have to be accommodated.

In an anthropocentric philosophy, all output should be viewed primarily in terms of its use for direct consumption by people. Management then should strive to serve the human values that all these uses embrace. On the other hand, under a biocentric approach, management should aim to maintain natural ecological processes as its prime objective, while keeping human impact at a minimum level and certainly subservient to ecological considerations.

There is no clear answer as to which attitude is right or wrong. Depending on the position one takes along this continuum, the end product of management will differ greatly. However, as resources become scarcer it is necesssary to seek the optimal position along this continuum in the context of each society. In other words, there is a need for development of management systems which would balance a variety of needs and goals, and this requires consideration of many objectives.

A great difficulty in developing such management systems lies in the conflict which is generated when many objectives are attempted to be realized simultaneously through planning and plan implementation. In public forest management decision-making problems in the face of multiple conflicting objectives occur in diverse contexts.

A common type of conflict arises when objectives other than commercial timber production , such as recreation and nature conservation are imposed on forest managers and planners. This situation is known as "multiple use". The choice of the optimal alternative is difficult, as these objectives usually to be maximized are not readily converted into monetary value, while entailing costs to be minimized. The basic problem facing the forest managers in this context is how to weight competing values against each other. National Parks are typical examples of this type of conflict. They involve management decisions which demand evaluation of multiple objectives outside the market system.

Another type of conflict arises between forest planning and management authorities and local planning and administrative bodies or individuals. This results because the former have general 'community-wide' objectives, while the latter have more specific local interests. Grazing demand on forest lands is a typical example of this type of conflict.

Conflict can also be generated between the forest planning system and organizations or individuals, who although not involved in planning are affected directly or indirectly by planning decisions. Exclusion of recreationists from forest lands has generated conflict of this type in many cases.

Finally, conflict may arise when new values and objectives or pressures for shift in priorities clash with a limited set of values and priorities, which have been incorporated into the planning system. Afforestation in the uplands of Scotland has generated conflict of this type, since it has clashed with the views of many groups of people and individuals, who are reluctant to accept landscape changes.

Resolution approaches to forest management conflicts can be of a technical form, such as cost-benefit analysis or may involve political means, such as persuasion or exchange within the planning system.

The mechanism of conflict resolution is characterized by two types of transformation (Baumgartner, Burns, DeVille and Meeker, 1975): transformation of perceptions and evaluation and transformation of options.

In the first case, resolution is achieved: 1) through restructuring alternatives and relationships between alternatives and their outcomes, that is transformation of the model of the system and 2) through re-evaluation of alternatives, that is transformation of preference structures.

In the second case, resolution is achieved: 1) by developing a new alternative that dominates the existing conflicting alternatives. This presupposes, however, that the dimensions of the existing alternatives are independent or positively interdependent. 2) by developing a compromise option with maximin properties. That is a new alternative, which combines advantages of the existing options, although it may be ranked lower with respect to each of these options.

Conflict resolution processes in public forest management may involve prioritization of objectives, trade-offs, development of more satisfactory options or re-formulation of the problem. Exclusion of certain values usually prevents conflict and has been done in forest management and planning situations. However, the resolution may be a temporary one, since the excluded values may create reactions to the results of planning. In any case, conflicts in objectives are never settled in abstract, but are settled temporarily in a particular social context. There is no standard mixture giving fixed weights to each value that can be projected in the indefinite future. Changing circumstances often force a change in the emphasis given to one value relative to another.

Obtaining knowledge about a conflict problem is not sufficient for resolution. It is also necessary to carry out procedures in order to resolve conflicts. Investigation and analysis of decision-making processes which occur in forest planning is of great importance. Forest planning and management system design play an important role in conflict resolution. This project is concerned with the design of a decision-making (decision support) system, which can help managers of public forests to resolve conflict in the multiple use context. The background of the problem that led to the initiation of this study is presented through the overview of Forestry Commission policy and management goals in the following section.

1.2 OVERVIEW OF FORESTRY COMMISSION POLICY AND MANAGEMENT GOALS WITH EMPHASIS IN SCOTLAND

The Forestry Commission is the State Forest Service of the United Kingdom formed under the 1919 Forestry Act. The Commissioners are appointed by the Queen on the recommendation of the Prime Minister and are responsible to the Secretary of State for Scotland, the Minister of Agriculture, Fisheries and Food in England, and the Secretary of State for Wales.

The Commissioners have a dual role. They act as the national Forestry Authority responsible for the entire forestry industry, both public and private, and direct the Forestry Enterprise, which is the public sector of the industry.

At the time the Forestry Commission was established only 5% of British land was wooded. During the past 65 years, afforestation on a large scale has taken place, thus increasing the total forested land to 10%. Although much has been achieved, the amount is still low compared to European standards. The European Community countries have on average 25% of their land covered by forests.

The extent of existing woodlands in Britain in 1987 is shown in Table 1 below:

Country	Thousands of hectares					
	Ownership Category					
	Forestry Commission	%	Private Sector	%	Total	%
Scotland	526	53	470	47	996	100
England	240	28	620	72	860	100
Wales	133	56	105	44	238	100
Great Britain	899	43	1 195	57	2 094	100

Table 1. Total area of productive woodlands in Britain (1987).

It is obvious from Table 1 that the bulk of Forestry Commission plantations are located in Scotland; 13% of Scottish land is now covered by forest. On theoretical grounds this amount could be increased to 30%. The figure was estimated by the Forestry Commission after taking into account physical and economic constraints in 1976. (Countryside Commission for Scotland, 1986). More practically, if we take the present annual rate of new planting, of the order of 20,000 hectares per year, by the end of the century only 4% more Scottish land will be forested, the total would reach 17%.

Most of the afforestation has been with conifer softwoods, mainly spruce, larch and pine. These species are very well suited to the exposed upland areas of Scotland and therefore grow fast. At present 90% of the Forestry Commission's forests is of conifers. Despite this, imports of wood and wood products account for 90% of the total wood consumption of Britain, at a cost of £4.5 billion a year (Forestry Commission, 1987a). This figure shows clearly the case for increased timber production to cover industrial demands and to reduce imports. In this context, the policy of creating predominantly coniferous forests can be justified. Considering that Scotland is Britain's most wooded country, and that 11,200 people are presently employed in Scotland's forests and related industries (Forestry Commission, 1987b), there is a strong case for even the National Forest Parks remaining timber growing enterprises.

Up to 1959, the objectives of the Forestry Commission were to establish and manage public forests and to aid the development of forests in the private sector; to promote the forestry knowledge through training and research; and to exercise the plant-health duties which were previously carried out by the agricultural departments in relation to forestry.

Recognition of the importance of the forests for uses other than timber were expressed in the recommendations of the Zuckermann Committee on Forestry, Agriculture and Marginal Land in 1957, (Forestry Commission, 1987c). According to these, the Forestry Commission should aim not only to establish and maintain a strategic reserve of timber, but also to promote the social aspects of forestry.

However, multiple use management was not a formal obligation of the Forestry Commission. Even the designation of Forest. Parks was originally an attempt to protect the forests characterized by high scenic quality, rather than make them accessible to the general public. This was stated by the National Forest Parks Committee in 1935, the year of designation of the first Forest Park in Scotland (Forestry Commission, 1935). The Committee had recommended that "use of the

Forest Parks should be confined to members of responsible organizations" and also that "the Commissioners should proceed cautiously and refrain from drawing undue public attention to what they are doing". Multiple use management was therefore exercised in a rather casual form (W.E.S. Mutch, personal communication). Forest managers would have liked to exclude walkers from forests, but especially in Scottish forests, they could not. The same was true of deer, which could not be excluded at any price or at a price that could be afforded. So, they called the deer and the walkers 'multiple use'.

Since 1960 multiple use management has been an obligation of the Forestry Commission (Forestry Commission, 1984a, 1984b, 1984c, 1984d, 1985).

This attitude was expressed in the Countryside Act 1967 (1968 for England and Wales). The Commission was granted the power then to open the forests to the public, to provide recreational facilities and also to plant and manage forests for amenity. It was, however, the policy statements in 1973 and 1974 that set out a statutory framework to ensure that forestry might form an effective land use harmonised with agriculture and the environment. The objectives of the Forestry Commission were re-defined then as follows (Forestry Commission, 1974).

The Forestry Commission as the Forestry Authority should :

1. advance knowledge and understanding of forestry and trees in the countryside;

2. develop and ensure the best use of the country's timber resources and promote efficiency and development in the home timber industry;

3. undertake research relevant to the needs of forestry;

4. combat forest and tree pests and diseases and initiate Plant Health Orders when appropriate;

5.advise and assist with safety and training in forestry; and

6. administer controls and schemes for assisting private woodland owners and, by so doing, encourage the practice of sound forestry, secure good land use and -where relevant- effective integration with agriculture, and ensure the use of forest management systems and practices which safeguard the environment.

The Forestry Commission as the National Forestry Enterprise should:

1. develop forestry and increase the production of wood for existing industries yet to be established by the extention and improvement of the forest estate;

2. protect and enhance the environment;

3. provide recreational facilities;

4. stimulate and support the local economy in areas of depopulation by the

development of forests, including new plantations, and of wood-using industry; and

5. in pursuit of these objectives and in the extension of the forest estate, further the integration of forestry and agriculture and manage the estate as profitably as possible.

Some general considerations however lie behind these policy lines.

Timber production remains the prime objective of the Forestry Commission , because it provides its major revenue. The aim is to maximize the net profit from the timber volume sold from its forests. The remaining objectives will be pursued subject to the financial resources available and to the primary objective of timber production. This implies a multiple use system, where recreation and all other uses have to be considered as supplementary, or complementary rather than competitive to timber production.

On these lines, the Forestry Commission encourages a limited range of activities within its forests to ensure that recreation conflicts neither with the actual productive process nor with conservation. The public is encouraged to enter all forests on foot, except in cases where access conflicts with obligations to lessors and tenants or with management requirements. Forest Parks remain under the designation status, while forests are generally projected as images of quiet resorts, where people can enjoy scenic beauty, air and exercise. On this basis the provision of facilities has been kept low. Small car parks, picnic places and waymarked footpaths are available free of charge. In the National Forest Parks which have an explicit recreational function by designation, some developments of a larger scale are also offered. Bigger car parks, information centres, camping and caravanning sites, forest cabins and forest drives, but these are intensive rather than extensive developments and are subject to charge. The Commission's policy is that a charge should be levied where specialised facilities are provided.

The current recreation policy, however, attempts to satisfy the less specialised , informal recreational demands of the general public. Thus, the recreational activities favoured are those creating the least impact on production forestry.

On the other hand, the Forestry Commisssion is not the only government agency concerned with the provision of recreation for the public in this country. The Countryside Commissions of England and Scotland, the Nature Concervancy Council, the Sports Council, the water and river authorities play a very important role too. Forests, nevertheless, offer a special attraction to the visitors. Sylvia Crowe (1973) pointed out three basic reasons for this. Their wildlife interest, their visual variety and beauty, their powers of crowd absorption. The estimate of 24 million visits made to

Commission land in 1986 reinforces this point of view (Forestry Commission, 1987d).

Indeed much has been achieved towards recreational development of the national forests since 1919, the year of the establishment of the Forestry Commission. The 67th Annual Report and Accounts 1986-1987 (Forestry Commission, 1987e) states the net expenditure on forest recreation and amenity to have been £6.6 million (1987 prices).

Consideration is now also given to the amenity of forests by implementing the principles of landscape design. Species for planting are chosen more carefully to promote diversity and create broadleaf areas; the natural landforms are taken into account, hard edges to plantations are avoided and care is taken, especially in the National Forest Parks, over the felling coupes to fit them into the landscape. The margins of the plantations along roads, paths and streams are left irregular, while open spaces are created within the plantations to provide good wildlife habitats. Conservation has come to be viewed as a dynamic process depending on change; by no means equated to unchanged landscapes and species. However, there is scope for more to be done.

Whether or not the Commission will have to continue on the same policy lines will depend on many factors which can not be predicted accurately at the moment. For example, it is not known how the present economic crisis and its consequent high rate of unemployment will affect the demand for recreation in the future. Neither is it known how private forest owners will respond to the new grant system for afforestation and maintenance of broadleaved woodlands. (Forestry Commission, 1988). Furthermore, it can not be predicted how new technology will affect leisure. Earlier research has shown that 25% of the visits to the countryside were made to woodlands, lochsides and riversides. (Costley and Mackenzie, 1982). Considering that most of the National Forests in Scotland combine all these habitats it seems certain that they will have to continue to accommodate recreational and amenity demands. The importance of the National Forests as scenic and recreational resources is likely to increase still further as people become more environmentally conscious.

The Commission will presumably be under further pressure to re-examine its attitude at the end of the century as most of the forests will be reaching maturity and decisions will have to be made with regard to forest land allocation schemes, a process already begun. The present policy calls for flexible multi-objective forest management systems to be devised and implemented, and adjustment to new situations would not be difficult.

The concept of multiple use forest management is not a new one. Forests as natural ecosystems do produce multiple products over a period of time, and this is generally acceptable. In practice, however, the concept of multiple use has been more a slogan or philosophy rather than an operational system. The main reasons for this, have been pointed out by several authors (Gregory,1955; Lloyd,1969; Clawson, 1974).

First there is the lack of input-output functions. That is functions,which describe what ecological and economic effect any increase or decrease in forest output or service would have on the other outputs or services. For example, in Britain, the conservation policy of the Forestry Commission stipulates the retention of trees which may be vital to some species of wildlife (Forestry Commission, 1972), but the extent of increase or decrease in terms of wildlife production or sustenance is not known. Also, trees, usually broadleaves, along water courses or around lakes are not harvested, because they help to maintain the water quality for fish or provide suitable conditions for wildlife species. But again, to what extent is the water quality improved, or by how much is wildlife production increased or decreased by such retention? It is therefore necessary to establish ecological and economic input-output relationships for any output or combination of forest outputs.

The second problem involves the estimation of prices or shadow prices for outputs or forest uses. To fix prices for wood and wood products is a difficult task, because trees are both capital and output in forestry, as there is usually a long time required for the outputs to be sold in the market. To fix prices or shadow prices for non-marketable products like recreation, wildlife, wilderness or scenic beauty is even more difficult and might not even make sense in many cases if it were done.

The third problem regards the distribution of benefits. In a multiple use situation it is very difficult to distribute income in an optimal or rational way. This arises from our inability to answer the question: Who pays the cost and who gains the benefit? For instance, wildlife conservation or recreation, which are of great value to society, are usually being offered free of charge in most forests and bring no income to the forest owner. In this context, cost-benefit analyses, which exclude them are liable to give false results.

Another problem related to multiple use situations is the social acceptability of feasible management alternatives. It is now widely accepted that economic efficiency alone, especially in public forests, does not constitute a single acceptable criterion for implementation of a management strategy. Quite a few forest controversies have been brought to public notice during recent years. They have all arisen from the neglect by foresters of social attitudes rather than from economic analysis.

Finally, the operational feasibility of the management plans proposed, and the scale at which multiple use planning and management should be applied need to be checked thoroughly. Budget limitations, operational capacity of the organization and administrative or bureaucratic procedures have to be considered as constraints in any operational system for multiple use forest management.

Generally, multiple use might involve different combinations of use intensity of different activities and implies three relationships between any outputs or services: competitive, supplementary and complementary. A competitive relationship exists, when an increase in the amount produced of one output, is associated with a decrease in the amount of another output produced. Outputs are in supplementary relationship when increase or decrease in one does not affect the other. A commodity may be introduced as sideline production to promote fuller use of the resources employed to produce some other main product. Finally, a relationship between two outputs is complementary if the production of the one benefits the production of the other.

In the case of national forests in Britain, where afforestation for timber production determines the amount of forest available for recreation, a supplementary product relationship exists. In other cases the relationship between different uses is complementary. For instance, trees offer screening advantages to recreation, while activities such as deer stalking may be beneficial to timber production by reducing forest pests. However, in the National Forest Parks, which are under higher recreational pressure, multiple use implies a competitive product form. For instance, a management strategy to increase timber production on pure economic grounds would encourage uniformity of species and age classes, shortening of rotation periods or even non-thinning management regimes in some cases. On the other hand, a management strategy to increase the provision of recreational facilities or to maintain scenic beauty, would promote diversity of species and age classes and probably extension of rotation periods.

To make the most of the available resources in competitive product forms calls for development of management systems which can deal with resource allocation for different competing uses.

Such systems could facilitate decision-making for resolving conflict by presenting the trade-offs between various alternatives in an explicable form.

In the following section the current planning and management system, which is applied to national forests is presented.

1.3 CURRENT PLANNING AND MANAGEMENT PROCEDURES IN NATIONAL FORESTS

Management generally operates at three levels: strategic, tactical and operational, which are not independent of managerial environment.

Strategic management searches the environment and consults with the interests the firm serves, to determine what activities it should be involved in, the extent of these activities and the criteria by which it should judge between various alternatives. In other words, the task of strategic management is to establish the objectives of the firm and the constraints imposed on the pursuit of these objectives. In the case of the Forestry Commission, decisions, such as the rate and location of new afforestation, the level of investment in state forestry and the financial criteria with which to judge alternative investments are responsibilities of the strategic management.

Tactical management attempts to satisfy the objectives of the firm set by the strategic management, to co-ordinate and allocate resources. It is concerned with the selection of courses of action which fulfil the objectives of the firm to the greatest extent. Investment programmes and the assessment of their long term consequences for the firm, as well as their short term effects in relation to production and resource requirements are components of this type of management. In the Forestry Commission environment tactical management is usually concerned with the selection of silvicultural treatments, such as choice of species, spacing, protective measures in carrying out the planting programs, timing and intensity of thinnings and fellings, as well as the type of markets to be supplied.

Operational management is concerned with exercising management and administration according to the given rules by tactical and strategic management. Tasks, such as deciding locations where operations are to be carried out and techniques, men and materials are to be employed and supervision of forestry operations are typical components of operational management.

The three management levels, as they operate in the Forestry Commission are shown in Figure 1.

The Headquarters is based in Edinburgh and is responsible for strategic planning and control. It also acts as liaison with the Ministers and other Government Departments, and it is responsible for central services, such as data processing.

The next management level operates at the Conservancies. There are seven such Conservancies. The Conservators are equivalent to regional general managers, responsible for tactical planning and control. Some operational functions take also place at the Conservancies such as contract control, i.e., industrial staff recruitment.

Operational planning and control is carried out at Forest District level. There are 70 Forest Districts, each managed by a senior professional forester. Although all management levels have an operational role in addition to their strategic and tactical one, the main operational function lies with the Forest Districts.

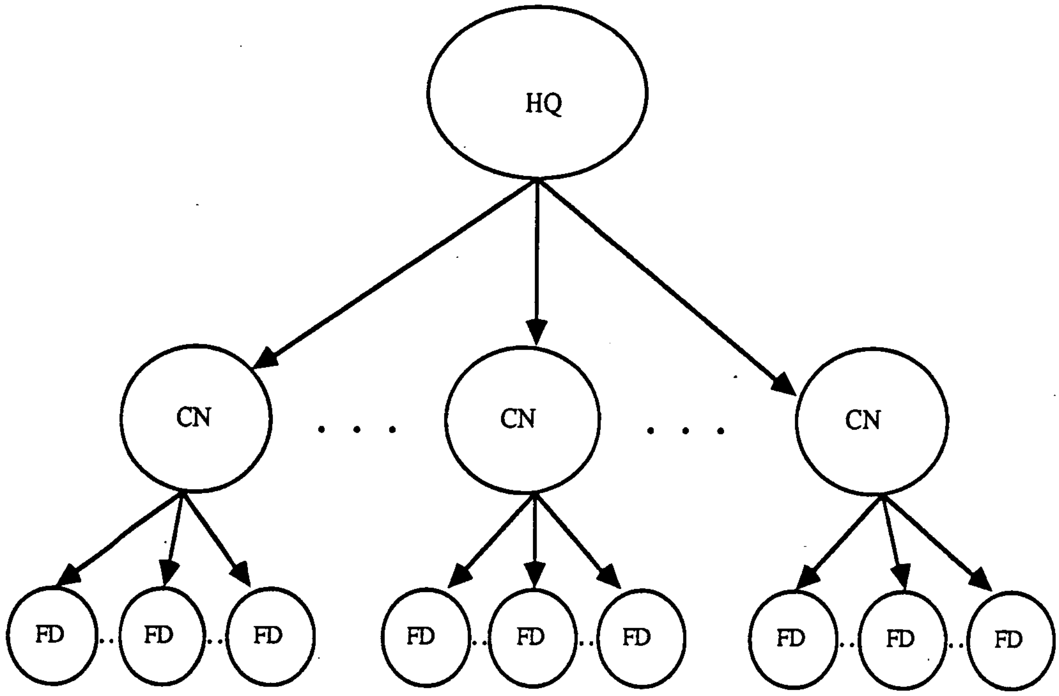
Up to 1960 all planning and control functions were performed through individual Forest Working Plans. In 1965 Conservancy Plans were introduced to co-ordinate the planning process, while the manual data base for growth prediction and financial forecasting was replaced by Computerised Yield Forecasting.

The planning procedures at Headquarters were integrated by means of a Corporate Plan, which was developed in 1970 (Wardle, 1970). In 1975, the introduction of the Policy Analysis and Review System at the conservancy level allowed modifications and interpretations of the national policy to be discussed formally. At the same time, a computerised Financial Control System replaced the manual one , but the submission of basic management and financial data was still manual. Finally, in 1985 the emphasis was put on a micro computer system which was developed in an attempt to help the district forest managers with data requirements for planning, control and administration; and also to provide data to the higher management levels.

Pritchard (1986) presented a good review of the system as it is currently being applied within Forest Districts. The system provides information in four areas: a) wages expenditure (including calculation of gross to net pay) b) operational performance of vehicles, machinery and equipment (VME); c) stocks of timber produced by Forestry Commission harvesting operations; and d) job costing (using data from a and b above).

In terms of multiple use planning and management, the current planning system of the Forestry Commission includes a Conservation and Recreation Branch at the Headquarters level and Recreation Plans at the conservancy level. The responsibility of the first is to formulate policy lines for the development of the recreational potential of

FIGURE 1. FORESTRY COMMISSION MANAGEMENT STRUCTURE



HQ:HEADQUARTERS = STRATEGIC PLANNING AND CONTROL AND CENTRAL SERVICES

CN:CONCERVANCIES = TACTICAL PLANNING AND CONTROL AND SOME OPERATIONAL FUNCTIONS

FD: FOREST DISTRICTS = OPERATIONAL PLANNING AND CONTROL AND OPERATIONAL ADMINISTRATION

the national forests within the Commission's interests and responsibilities. The second have been introduced to aid the implementation of the policy at the regional level. A recreation planning officer is appointed in each Conservancy to co-ordinate forest recreational developments.

1.4 OBJECTIVES OF THE PRESENT STUDY

There is an apparent lack in the current planning framework of a decision support system for tactical management in multiple use forests, where non-marketable products and services also have to be accommodated over time. That is a system which will help tactical managers in their deciding on the allocation of forest resources while simultaneously trying to satisfy over time the longer term multiple objectives, within physical and operational constraints. The FORM (FORest Management) model, which has been the result of this investigation is such a decision support system to help managers come to better decisions.

The system is computer -based and its basic features are:

1. It leaves the forest managers with full control of the decision making process; so that they can provide their own answers and solutions to forest resource allocation problems.

2. It enhances the forest managers' abilities by providing analytic support for exploring new alternatives (trade-offs).

The Queen Elizabeth National Forest Park, which forms part of the Aberfoyle Forest District in Central Scotland has served as the study area; it is especially suitable since it is designated to be managed for multiple objectives.

The rest of this thesis is organized in the following way. Chapter 2 presents a discussion on decision-making research which has been carried out in forest management. Chapter 3 describes the forest response relationships (models) currently included in FORM. Chapter 4 presents a classification-discussion of multi-criteria decision-making methods along with the method selected for the optimization component of FORM. Chapter 5 includes a general description of FORM and a presentation of the subject area, which was used to implement FORM. Components one and two of FORM are described in chapters 6 and 7 respectively, while components three and four are described in chapter 8. Finally, chapter 9 includes general conclusions drawn from this research, as well as some areas where further research will improve the performance of FORM.

CHAPTER TWO. REVIEW OF DECISION-MAKING RESEARCH IN FOREST MANAGEMENT

2.1 INTRODUCTION

The function of management is to make and carry out decisions in order to meet people's objectives. It is the decision-making process of management which creates resources, by implicitly valuing attributes of things which lead to exchanges or trade-offs or both. Decisions in forest management usually relate activities, which make varying demands on limited forest resources and have differential impact on the result.

The central problem of forest management can therefore be viewed as using the resources available to achieve the objective or objectives of the forest firm to the greatest possible extent, considering any restrictions placed on this pursuit.

The interaction between the alternative options under consideration in forest management is a complex procedure, as in most cases the choices are dependent on the same resources and identification of the best combinations is a very difficult task. Difficulty is also increased by the fact that decisions have to be based on limited information. This is either because information about forest resources is lacking or when available may be ignored, because its complexity places it beyond comprehension. Various analytical tools have been devised to resolve complexity and make information available. Mathematical models have been shown to be the most useful in dealing with the dynamic complex nature of forest ecosystems.

Two distinct phases can be recognized in the history of decision forest management research. The forest managers of the sixties and early seventies dealt mainly with efficiency and effectiveness problems considering a single criterion. The management of late seventies and eighties is mainly characterized by the emphasis placed on multiple criteria in the evaluation of the forest resources. The rest of the chapter is organized into two sections corresponding to these two phases. Section 2.2 presents work carried out with respect to one criterion, while section 2.3 refers to multiple criteria forest-decision-making research.

2.2 SINGLE CRITERION FOREST MANAGEMENT PROBLEMS

Cost-benefit analysis is one of the analytical tools management scientists have used extensively in the economic evaluation of natural resources.

Marglin (1967), stated the goal of cost-benefit analysis as the maximization of utility subject to whatever constraints the economic and political environment imposes. Technically, the method involves identification and comparison of benefits and costs of a set of actions incurred to upon society.

The basic concepts used in cost-benefit analysis draw from Welfare Economics theory. The welfare function which is attempted to maximize is the utility-possibility frontier. This frontier represents the maximum combinations of utility which the economy is capable of producing. Each combination on this frontier is Pareto optimal, that is, no person is made better off without making someone else worse off. Any level of social welfare is represented by a social welfare indifference curve. There is an infinite number of such curves. The point of tangency between the utility frontier and a social indifference curve identifies the maximum combination of utilities which brings society to the highest possible level of social welfare.

The Pareto optimal criterion introduces conservatism in evaluating resource allocation. In the real world the decisions made are rarely Pareto optimal. To overcome this problem, economists have developed the concept of Potential Pareto improvement (Convery, 1977). A Potential Pareto improvement exists when individuals whose welfare has improved compensate those whose welfare is deteriorated, even if such compensation is not actually paid. Cost-benefit analysis uses this concept in the following sense. If the benefits of a proposed alternative scheme exceed the costs, then other things being equal, it should be undertaken, even though those who benefit from it do not actually compensate those who lose. This assumption is a serious drawback of the method, as it implies that the existing income distribution is optimal.

The biggest difficulty, however, in cost-benefit analysis is associated with the derivation of social welfare functions. Personal utility is hard to estimate and the combining of individual welfare impacts is far too complex.

Two notions were introduced to circumvent these problems which form the basis of every cost-benefit study. First is the notion of 'consumer surplus'. This is defined as the difference between the maximum amount a consumer is prepared to pay for a certain good rather than go without it, and the actual value of this good at the good's competitive market. The sum of actual payments and consumer surplus defines the second basic concept in cost-benefit analyses, that is the 'willingness to pay'.

If labour and capital are fully employed, under perfect competitive market conditions, the market prices reflect adequately the maximum willingness to pay for any forest output. However, this is not generally the case and the valuation process of the various forest outputs is therefore a complicated procedure. Cost-benefit analysis gave rise to a considerable amount of research, regarding valuation of non-marketable benefits, when such benefits have to be incorporated in the analysis. Outdoor recreation especially has been the most extensively non-marketable item investigated, and various techniques have been developed as a result of this effort. Of these, the contingent valuation method (CVM) and the travel-cost method (TCM) are the most popular.

CVM attempts to value a resource by asking people to respond to a hypothetical market situation, either by stating quantitatively their willingness to pay (WTP) to consume the resource of concern or their willingness to accept (WTA) as a compensation to forego it (King, Bugarsky and Shaw, 1986; Hanley and Common, 1987; Willis and Benson, 1989). An estimate of the total value of the resource is then obtained by aggregating individual bids. The total value is usually considered as the sum of the actual use value (current and future) and the existence value.

The problems related to this method refer to the appropriate measure of valuation (WTP or WTA), the aggregation of bids and the bias of results. Brookshire, Randall and Stoll, (1980), argue that the WTP criterion is a more reliable means of data collection than that of WTA. The same authors, however, support the use of WTA in cases where the alternatives under assessment involve a decrease in a natural resource. Aggregation of bids may generate problems, because of the weighting procedure of individuals' valuation in summing total bids. Bias finally arises from many sources both conceptual and practical. The notion of the hypothetical market for example, may introduce bias as bids in hypothetical markets are not the same as bids in actual markets. Practical aspects which may result in biased results relate to the sampling method, the statistical analysis and the structure of the questionnaire.

King *et al* ., (1986), support that if the existence value of the resource forms a large proportion of the total value CVM is more appropriate to use than TCM.

TCM originated by Clawson (1959), attempts to measure the total willingness to pay for a recreational site as given by the area under its imputed demand curve. This area measures the total willingess to pay and therefore the value of the site itself. The demand curve is estimated from the behaviour of the visitors to the recreation sites as indicated by the cost of their travelling to the sites.

The method involves a series of calculations of the potential visitor response to the hypothetical imposition of incremental fees at the entrance gates. The model relates visits to the site of interest to various explanatory variables, travel cost, income, population size and index of substitution of site. Changes in visit quantities (reduction) are estimated on the basis of the inverse relationship of visit rates of population centres and distances from the recreation site. When an assumed increased cost occurs, the visit rate from any centre is expected to fall to that of centres further removed.

A serious bias introduced with this method is caused by the failure to capture the effects of travel time in the model. Cesario and Knetch (1970), in the frame of the household production context (Becker, 1965), suggested as a remedy to this that distance be considered as a function of time as well as monetary cost. Improvements to the estimation of demand curves have been introduced by many researchers in the field. Brown and Nawas (1973) and Gum and Martin (1975), showed that the efficiency of estimation of recreation demand function parameters can be improved by considering individual observations rather than zone averages. McConnell (1975), suggested that for recreation demand functions to be consistent with the concept of utility maximization not only the time in transit, but the total time required for completing the recreation activity must be considered. Also the unit of measurement should be the trip or visit and not the user-days, while specification of the demand function must be done a priori, so as the price slope can change as income changes.

Cesario and Knetch (1976) produced a non-linear version of the travel-cost method, which estimates both economic benefits and use of any site or system of sites under a range of conditions for outdoor recreation. Substitution effects of price changes and a surrogate for time cost as well as money cost are considered in their model. Bowes and Loomis (1980), suggested generalized least squares instead of ordinary least squares, when estimating parameters of demand curves and benefits from samples of unequal size derived from unequal zone populations.

Hof and King (1982), furthermore, showed that for multi-site travel cost models there is no need to estimate demand functions for all sites. One site's demand curve can be estimated and utilized at a time when one price change is involved and cross-price terms are symmetrical. Also King and Hof (1985), studied different social-psychological experience types of anglers in relation to benefits of fishing. They found that different experiences may not be important for estimating the total benefits foregone by site elimination, but are important for decisions which would alter a site's experience mix or for estimating benefits of a new site with a different experience mix than existing sites.

Vaughan and Russell (1984), used a stochastic approach drawn from statistical ecology to establish physical regressors as proxies for travel cost based activity prices. These can be used to estimate recreation activity demand equations. Physical resource availability, such as number of lakes per unit area in a region is inversely related to the expected travel cost from any arbitrary point in the region to the closest recreation site.

Once all benefits are valuated in money terms, cost-benefit analysis proceeds to comparison of alternatives, which is attempted using economic discounting type indicators. These may be either the net present value (NPV) indicator, or the cost-benefit ratio (CBR) or the internal rate of return (IRR). NPV is the difference between discounted benefits and discounted costs. CBR is the ratio of discounted benefits over discounted costs, while IRR is the discount rate at which the discounted benefits become equal to discounted costs.

An alternative is financially viable if NPV is positive or CBR greater than 1 or IRR greater than the discount rate. When alternatives are independent and operate in an environment with no operational constraints all three indicators lead to similar decisions. When, however, the alternatives are mutually exclusive and budget constrained, all three criteria appear to have drawbacks and selection should be attempted with care. For mutually exclusive alternatives, the NPV indicator is more preferable, although the alternative with IRR greater than the market rate of interest may be acceptable. NPV compares alternatives automatically with any value foregone (opportunity cost) without investing money in the market. Comparison with the IRR is done on the basis of the 'accept-reject' decision rule. When funds are limited CBR appears superior to NPV , but it does not indicate the true magnitude of net benefits. On the other hand, IRR is a pure number and comparison is easier, but it requires knowledge of the market rate of interest.

Valuation of non-tangible benefits in money terms, which has been attempted within the frame of cost-benefit analysis has created debate between analysts, who at times have proposed various ways for trade-offs in different decision-making contexts.

Johanson (1984), derived cost-benefit rules for timber management in a multiple use national forest management framework by incorporating external effects both in consumption and production. Canham (1986), suggested that a measure of comparing timber with recreation might be actual expenditures. He also argued that it is not necessary to include consumer surplus in order to estimate trade-off values. According to Kellert (1984), the most serious defect of cost-benefit analysis is to generate prices for unquantifiable goods. He argued that cost-benefit analysis is not suitable to assess the importance of intangible environmental benefits for two reasons: First, it introduces bias towards consideration of quantitative factors. Second, assignment of qualitative assessments to intangible environmental values typically results in grossly imprecise evaluations and incomplete specification of the values at risk. He, alternatively, suggested establishment of standardized numeric procedures for measuring all environmental values empirically. Loomis and Walsh (1986) in their reply to Kellert's assertions argued that Kellert's approach is not an effective substitute for money measurements, when performing environmental assessments. However, they pointed out that approaches of this type could improve the conceptual basis of bio-economic techniques and therefore should be viewed as complements rather than as substitutes for economic evaluation of non-tangible benefits.

Walter (1978), published another view on this subject. He pointed out that the problem of multiple use management arises because of attempts to treat marketable services as non-marketable 'public goods'. He classified the forest services according to methods of payment levied (direct payment for products of the resource/licence fees for access/user fees/free access). In pricing multiple use land resources he considered two types of demand, special interest areas (SIA's), such as historical sites, waterfalls and small lakes and generalized access areas (GAA's), such as those offering hiking, fishing, environmental quality and wood. He finally suggested the following revenue structures as an aid in achieving rational economic management of marketable land-based multiple use services: budgetary allocations out of general revenues (taxes); monies obtained from bids or leases for an identifiable SIA; permits for access to forest or other land based zones; permits for harvest of a 'population' (trees, grass, fish, ungulates); user's fees for use of a marketable service (camping, picnics, boat launching); and road tolls.

When a certain objective or objectives (utility functions) are to be maximized or minimized in a production context, subject to various forms of resource constraints mathematical programming techniques are more appropriate to use as they provide a better insight into the production problem.

Linear Programming is one of the first mathematical programming methods which have considered for forestry planning and management. It is not surprising that harvest scheduling problems is the theme of the majority of applications as timber production has always been the main justification of forest mangagement.

A harvest schedule or cutting schedule is required to implement forest-level management planning. This lists the stands to be harvested each year of a pre-specified planning horizon. It also contains data on the types and intensities of harvests to be carried out in each stand and a timetable for regenerating areas both unproductive and stands scheduled for harvesting. The operating characteristics of the forest, such as annual harvest, annual cash flows, age-class distribution in any given year and the structure of the forest at the end of the planning horizon are direct outcomes of the activities specified in the harvest schedule.

Among the first attempts to illustrate the usefulness of linear programming in developing optimal harvest schedules in sustained yield management were the works of Curtis in 1962 and Loucks in 1964. Curtis solved two problems related to maximization of wood and maximization of present value of a forest property at a 5 percent discount rate. Loucks used two hypothetical cases. The first maximized the volume to be cut, subject to area constraints and yield flows. The second minimized the area to be cut assuring a specified yield for each cutting period.

Johnson and Scheurmann (1977) in their attempt to synthesize work on timber harvest optimization distinguished two types of models in terms of their mathematical form. The main difference was traced in the definition of the activity variables. Model I assumes that each activity variable specified as a certain pattern of forestry operations occurs on a particular land area over the entire planning period. In Model II formulation each activity variable refers to a particular area from the regeneration time until the harvesting time or until it is left as ending inventory at the end of the planning period. Both models maximize the present value of all future cash flows. In Model II, however, if a value or revenue or costs are associated with hectares of forest land which are left unharvested as ending inventory, the objective function should also include as activity variables these hectares that form the ending inventory. Model II formulation results in larger numbers of area constraints, while generally the number of activity variables required in Model I formulation is significantly larger than that of Model II.

Typical works of Model I formulation are the RAM model (Resource Allocation Model) developed by Navon (1971) for harvest scheduling in public forests, the

MAXMILLION model for forest industry (Ware and Clutter, 1971; Clutter, Fortson, Pienaar, Brister and Bailey, 1983) and the work of Kidd; Thompson and Hoepner, (1966) on forest regulation management.

RAM and MAXMILLION models, which have been used in North America, the country of their origin, have almost the same theme: maximization of present value of all future cash flows , subject to area , harvest acreage, regeneration acreage, harvest volume and cash flow restrictions. MAXMILLION, however, does not base regulation of the forest system on the 'target forest' and 'normal stocking' concepts (Ware and Clutter, 1971). The constraints involve per period regeneration acreages, yields and area limits. The model consists of the 'appraisal phase', whereby wood flow and present worth of possible temporal cutting patterns of each unit are evaluated and the 'scheduling phase', whereby the optimal cutting pattern by cutting units is assigned.

RAM was criticised much by Chappelle, Mang and Miley, (1976) and Chappelle (1977) with respect to silvicultural management, socio-economic, spatial and computational restrictions built into the model. These authors pointed out that the model does not really answer the question of what mix of timber and non-timber goods and services should be produced. It answers questions of how and when stands should be scheduled for cutting once it has been decided that they should be harvested and also the expected level of allowable cut given the many assumptions of the model.

Nautiyal's and Pearse's work (1967) which involved optimization of the harvest schedule of an irregular forest during each conversion period to sustained yield is typical of Model II formulation.

Harvest scheduling problems in their linear programming form are usually very large problems including several thousands of variables and several hundreds of constraints. The combinations also which have to be tested for the selection of the optimal solution is very large. That is, if a forest is considered of having N number of management units and M number of management regimes are possible in each unit , then the number of possible combinations to be tested would be equal to N^M. For example, if N=6 and M=7, the number of possible combinations to be tested for identification of an optimal solution would be 279,936.

Liittschwager and Tcheng (1967) discussed formulation and computational results of a very large forest scheduling problem involving 1166 compartments to be assigned for a single cutting over a period of 24 years. The problem formulation resulted in 28,000 variables and 1,200 restraint equations. They applied a decomposition approach to solve it and reduced it to 930 subproblems. They reported very slow convergence, but the yield at the 240th iteration was 99.9% of the the total yield at the end of 930 iterations. Therefore, the algorithm could provide very good operating results with only 240 iterations.

Quite pioneering design for its time was the work of McConnen, Navon and Amidon, (1966). They produced the MIADS model to assemble and display map information, generate data for a linear programming harvest schedule model, generate optimal solutions and use the computer output to assist the forest manager with the on-ground operations.

An optimal sustainable forest harvesting model was presented also by Rorres in 1978. His model formulation is very intriguing. He described the growth of the forest between harvests with Usher's growth model (1966,1976) based on Leslie-type matrices and optimized yield using linear programming by determining the number of live trees to be cropped in each size class.

All the work reported so far has been carried out in North America. In Britain, linear programming applications to forestry are very scarce. Wardle, in 1966, formulated two forest management problems as linear programming models, the development of the optimum felling program of a forest and the wood supply to particular markets. The only other work in this field is Jackson's effort in 1971, who modelled the U.K. forest products sector as a whole, using linear programming.

Two reasons might have contributed to the scarcity of applications of this type. The first may involve the vast amount of data information a linear programming model requires to sufficiently approximate real situations. The second may involve the assumptions of linear programming models. These include linearity of objective and constraint functions, additivity and divisibility (Chappelle, 1977; Bell, 1977). Linearity implies that changes in outputs are proportional to changes in activity variables. For example, if 1 ha of forest land produces 12 m^3 of wood under some activity, 10 ha would produce 120 m^3 under the same activity.

Additivity is implied through linearity. Practically, it means that the total utility produced by any two activities would be equal to the sum of the utilities of the individual activities. That is, if regime A results in 10 recreation visitor-days per ha and regime B in 5 recreation visitor-days per hectare, the combination of A and B would result in 15 recreation visitor-days per ha. In other words, A and B are assumed independent.

Divisibility implies that activities can be divided in smaller parts. For items like number of people or animals, fractions are not so meaningful and rounding of values is usually attempted. Yet, there are cases where unacceptable errors may be generated through a rounding procedure. In such cases linear programming should not be used. Instead other mathematical programming approaches, like integer programming can be attempted. Despite these limitations linear programming models have been produced for several types of forestry problems, quite successfully in most cases.

Optimal growing stock problems are, like harvest schedules, another class of forest management problems dealt with by linear programming. Adams and Ek (1974) looked at the optimization of forest management aspects of uneven-aged forests. They considered determination of the optimal sustainable distribution of trees by diameter class for a given initial stocking level and determination of the optimal cutting schedule for converting an irregular stand to a target structure. They maximized value growth over a cutting cycle using non-linear equations for stand table projections. The optimal conversion schedule was found for the maximum present worth.

Buongiorno and Michie (1980), developed a matrix model to predict long-term growth of uneven-aged stands under various management regimes. They used linear programming to maximize net present value of future periodic harvests for various sustained yield management regimes. Their model allowed for determination of the economic level of harvest and residual growing stock and also optimum cutting cycle. They assumed, however, fixed prices, while their growth model did not consider species composition.

Chang (1981) used static optimization techniques to maximize the forest value of uneven-aged pine stands, while simultaneously determining the optimal growing stock and cutting cycle. Chappelle and Nelson (1964) attempted marginal analysis to estimate optimal stocking levels and rotation ages of loblolly pine stands.

Other forestry problems dealt with by linear programming include tree improvement, timber stand regulation, prescriptions of the marking, financial analysis, planning-logging operations, woodland-mill interactions, wood processing, wood turning and sawmill management. A detailed review has been presented by Field in 1977.

2.3 MULTIPLE CRITERIA FOREST MANAGEMENT PROBLEMS

More realistic models of forestry problems can be produced with multi-objective programming methods, since multiple usually conflicting objectives are typical of forest management situations. Multiple use forest management is the best known forest problem, where multiple objectives must be considered and has formed the theme of many studies.

Gregory's economic approach to multiple use in 1955 is one of the first theoretical models for resource allocation, when multiple objectives are considered. However, his approach requires conversion of intangible benefits into money value in order to maximize a composite single objective of money return using marginal analysis. An extended theoretical form of this model, which includes all land instead of a particular tract of land, in a resource allocation scheme was presented by Hagenstein and Dowdle in 1962. Elaboration of mathematical techniques permits nowdays to deal with many objectives in natural resources allocation schemes on their own terms. Many authors since that time have worked on various concepts of multi-objective forest management problem formulation.

Bertier and DeMontgolfier (1974) used outranking relationships (Roy's theory, see Chapter 4) to deal with a specific problem related to a forest environment. The problem regarded a suburban highway design through a forest. Their multi-criteria formulation provided a justification for rejecting all the 'through' alternatives, so that no highway should be built through the forests due to negative environmental impacts. At about the same time (1973), Field discussed the advantages of goal programming for forestry applications in comparison to traditional single objective programming. He illustrated use of goal programming in two hypothetical forestry problems. Since then, goal programming has been used in various forest decision-making contexts.

Schuler and Meadows (1975) and Schuler, Webster and Meadows, (1977) used goal programming to allocate land to different alternative uses in the Mark Twain National Forest Park in Missouri. Bell (1976) discussed the potential of goal programming and associated pitfalls through an example in land use planning. Bare and Anholt (1976) demonstrated use of goal programming as a decision -making aid in selecting forest residue treatment alternatives. Arp and Lavigne (1982) also applied goal programming to a multiple-use forest problem using variable planning horizons. Other goal programming applications include the works of Dane, Meador and White (1977), who examined trade-offs in land use planning and Walker (1985), who applied a modified version of goal programming(interactive derivation of ordinal and cardinal weights) to a hypothetical reforestation budget allocation problem.

However, multiple-use forest management was approached in a more conventional way by several authors.

Kent (1980) stressed the potential as well as the limitations of single objective linear programming as an analytical tool in the process of plan development in a multiple use land management framework. Single objective linear programming was also used by Osteen and Chappelle (1982) to achieve specified demands for timber and wildlife, while meeting a land erosion constraint in the Kalamazoo river basin of Michigan. Connaughton and Fight (1984) estimated trade-offs for national forest planning in their single objective linear programming model through systematic variation of the objective of any output for each alternative.

Leuschner, Porter, Reynolds and Burkhart, (1975), in their multiple use model used timber yield as the objective function to be maximized and expressed all other objectives as constraints. Their model is comprehensive regarding inclusion of activities. However, it suffers from several drawbacks. The objectives expressed as constraints have infinite weight in relation to the objective appearing as objective function. The objectives stated as constraints are assumed of equal importance. Finally, the problem appears to have no solution if all objectives expressed as constraints can not be satisfied simultaneously.

Some other approaches to multi-objective forestry problems are also worth presenting.

Brown (1976) used alternative analysis in his multiple use forest management model. Response of various alternatives in relation to outputs was simulated and the manager was presented with the trade-off results. Physical and dollar effects were expressed as totals or changes from totals.

Boyce (1977,1978) produced DYNAST-MB and DYNAST-MT to generate alternatives for multiple use management of eastern hardwood forests, using cybernetics, that is feedback processes which force the system towards an ideal goal. Bell (1979) experimented with a combination of simulation and utility theory in solving a forest pest problem with multiple objectives in Canada.

Steuer and Schuler (1979) in their attempt to overcome the drawbacks of goal programming approach applied Steuer's interactive multi-objective linear programming method(see Chapter 4) on the Mark Twain National Forest Park case. Mendoza, Bare and Campbell (1987), used the Hop Skip Jump (HSJ) method originated by Brill, Chang and Hopkins (1982), in their multiple use planning model. They reported that the method can not be used as an optimization tool, but proved useful in generating satisficing alternatives. Thus, inadequately formulated MOP problems can focus on dominated rather than on nondominated solutions which may be better alternatives.

An interesting combination of goal programming and input-output analysis for multiple use forestry was presented by Chang and Buongiorno (1981). However, their model provides only static analysis of the problem, although it considers relationships between management activities. Also trade-offs between goals of different priorities can not be computed during the solution process. Interactive multi-objective linear programming was the method used by Jordi and Peddie (1989) to determine the stocking capacity of a small game reserve, while maximizing utilization of the park by animals, game viewing potential of the park and revenue derived from the park.

A serious problem which may arise in multi-dimensional problem formulations is associated with the convex combinations of discrete alternatives usually formed through the iterative interaction between an analyst and a decision-maker. This problem was discussed by Hof, Marose and King (1985), who showed through a case study that highly variable and unpredictable errors may be involved in the predicted cost of convex combinations of alternatives and the further apart the alternatives are, the stronger the potential for substantial error.

Game theory and multi-attribute utility methods also have been demonstrated in a number of forestry problems. Rideout and Hof (1987), used a game theoretic approach to the cost allocation problem of multi-purpose forestry. Teeter and Dyer (1986), presented a multi-attribute utility model for evaluating alternatives when risk and efficiency impacts facing the forest fire management planners. Multi-attribute decision theory was also the basis in Hybergs' application (1987), to a non-industrial forest with two management objectives, timber income and aesthetic benefits.

Harvesting schedule problems were approached from the multi-objective view point in a number of studies. Hof, Pickens and Bartlett, (1986), used the MAXIMIN concept of fuzzy programming to maximize the minimum harvest at any one time period across all time periods in the planning horizon, during the conversion period of an unregulated forest into a regulated one, subject to nondeclining yields. This approach was shown superior to the traditional one of maximizing profit, subject to nondeclining yields only when the latter resulted to increasing harvesting flow patterns. However, it did not prove very useful in situations where the initial age structure of the forest did not contain trees in the early time periods, because it indicated harvesting of immature trees.

Field, Dress and Fortson (1980), attempted harvest scheduling in a multi-objective framework, using single objective linear programming and goal programming in a complementary fashion. They argued that formulating a goal programming model from the single objective linear programming model and checking the solutions subsequently with the single objective linear programming model, non-inferior goal programming solutions are guaranteed. Hotvedt, Leuschner and Buhyoff (1981) used also a complementary linear and goal programming approach for harvest scheduling models, but they applied a heuristic weight determination procedure to solve the goal programs.

Determination of optimal thinning and harvesting plans for a forest with a large number of different stands was solved with a two stage mathematical programming approach, involving dynamic programming and multiple objective linear programming by DeKluyer, Daellenbach and Whyte (1980). The first stage (dynamic programming) was used to identify the efficient thinning and clearfelling regimes for each type of stand, thus reducing the number of viable cutting options for any specified stand. These efficient regimes then were used in the multiple objective linear programming model to obtain optimal policies for the whole forest. The desirable feature of this approach is that it results in a small size model, which is more manageable.

Allen (1986) attempted to solve a multi-objective regional forest planning problem in Tanzania with a generating technique, the non-inferior set estimation method. The method was rather well suited in the framework of her study, since multiple forest users were inaccessible to be consulted during the solution process, thus making other methods less desirable candidates for this type of problem.

Some forestry problems have been formulated using the concept of the stand as a set of a restricted number of states. These problems were solved by other types of mathematical programming. Rose, Leary and Chen (1981), maximized volume based on a modified Richard's growth model through optimal thinning regimes derived by dynamic programming. Hellman (1982), maximized physical yield of an uneven-aged forest through a dynamic programming model, which bases cutting on the generation of a function of the age of the tree, that specifies the fraction of all trees of that age to be felled per unit time. His model formulation reduces the problem eventually to a single non-linear programming problem. Kao (1982), used a probabilistic format of dynamic programming to determine joint optimal stocking and rotation under risk. He considered stand management in a finite horizon context. Lembersky and Johnson (1975), dealt with the same type of problem, but they used infinite horizon and expressed uncertainties in a Markovian decision process. Several other authors (Amidon and Akin, 1968; Brodie and Haight, 1984; Kao and Brodie, 1979; Brodie and Kao, 1979; Brodie, Adams and Kao, (1978); Roise, 1986a; Roise, 1986b; Riitters, Brodie and Hann, 1982) produced dynamic programming models. Their theme has been the same, that is thinning and rotation age at the stand level.

It becomes clear from the work presented in the previous paragraphs that mathematical programming techniques can be used as analytical tools to solve various types of forestry problems. However, linear programming and related techniques should not be viewed as decision-making substitutes. Indeed their value stems from their potential as a means of generating information. Decisions are made and should be made by people. Reliability of input data is the main problem associated with these tools and this must be the focus of further research. Decision-makers would then develop confidence on the information generated, when using them as an aid in their decision-making process.

CHAPTER THREE. FOREST MODEL LIBRARIES

3.1 INTRODUCTION

Forests are sources of many goods and services for the people. They have the capacity to provide timber, forage, recreation opportunity and visual amenity either singly or in combination. The level and mixture of forest outputs may be decided depending on management orientation. That is, a forest manager on behalf of the firm may decide to produce a certain volume of timber, provide recreation opportunity for a certain number of people and maintain a number of distinct habitat types which are valuable for wildlife species. In order to achieve objectives like those he must know what inputs are needed to produce certain outputs or, in other words, he needs to have forest response functions or models. These functions can then be used in an integrated forecast model, so that he will have information output related to his decision variables suitable to insert in a 'choice' model. Such an integrated forecast model (FORM_CFGENS) is the subject of chapter 7.

In this chapter, the response models presented are those currently included in FORM. These involve timber, dispersed recreation, water-based recreation and deer stalking functions. The method of deriving timber production functions can be generalized to any British state forest. The dispersed recreation, water-based recreation and deer stalking models can be used only in conditions similar to those used for their derivation. The last two sections on forest conservation and budgeting describe not models, but quantification procedures incorporated in FORM.

3.2 TIMBER

Timber worldwide is considered an important product of the forest. The production process begins with the establishment of the forest, either naturally or artificially by planting and ends with the removal of trees in the form of logs, pulpwood or some kind of raw roundwood. Formally, the process can be grouped in five stages (Teeguarden, 1979): 1) regeneration 2) cultural treatment of growing stock 3) harvesting 4) conversion to wood products and 5) marketing.

Since the timber management objective in public forests is usually expressed in non-monetary terms, that is as maximization of physical yield of timber, only the first three stages are of interest in the context of this investigation.

In particular, timber management decisions are related to the timber output, that is the output of the harvesting process which is a function of the growth of trees. Tree growth is quantified in terms of height, diameter and volume. Of these characteristics, volume is the most important from the management view point.

Merchantable volume is conventionally defined as stemwood of at least 7 cm at diameter breast height (d.b.h.) overbark. Timber management is performed on stands of trees rather than individual trees. In forest silviculture, stands are classified into two groups: even-aged and uneven-aged.

The majority of British forests are even-aged and therefore only this type has been included in this study. The life cycle of even-aged stands has a beginning and end, like individual trees.

Volume increment is represented in the forest literature by two modes: the current annual increment (CAI), which is a curve showing the annual volume increment at any point in time and the mean annual increment (MAI), a curve showing the average annual volume increment from planting to any point in time. The cross point between the CAI and MAI curves defines the maximum average rate of volume increment, which a particular stand can achieve, irrespective of the point of time at which this is attained. This point denotes the yield class. For example, if the maximum MAI of a stand is 12 cubic metres per ha, its yield class is 12. In British forests, the range of maximum mean annual increment varies with the kind of species and extends from 4 cubic metres per ha for broadleaves up to 30 cubic metres per ha for some of the commercial conifers. Yield classes are generated by splitting the range for each species into steps of two cubic metres per ha, per annum and numbering the steps with even numbers accordingly. Yield classes are used primarily to predict the future rates of growth of stands. Models of stand growth and yield in tabular format have been constructed by the Forestry Commission Research Station for almost all forest species and yield classes in Britain for a variety of thinning regimes and spacings. These are known as yield models and constitute the chief timber management tool (Edwards and Cristie, 1981).

The information contained in the yield models is classified in 6 groups. The first group contains 1 column with the age of stand (years), that is the number of growing seasons which have elapsed since the stand was planted. The second group also contains 1 column with the top height (metres), which is estimated as the average height of a number of top height trees in the stand. The third and fourth groups contain 5 columns, each with the same set of variables, but they refer to the maincrop after thinning and yield from thinnings respectively. The variables include: a) trees per ha. In the third group, these represent the number of live trees left in the stand per ha, at a given age, after any thinnings have been extracted. In the fourth group, this variable refers to the number of live trees in the stand per ha, removed in the thinnings. b) mean d.b.h. This is the quadratic mean diameter, in centimetres, that is the diameter of the tree of mean basal area, measured at breast-height (1.30 metres above ground level). c) basal area per ha. It shows the sum of all the overbark breast-height cross-sectional areas of the individual trees, in square metres per ha. d) mean volume, which is the average volume of all individual trees in cubic metres. e) volume per hectare. This is the overall merchantable volume in cubic metres, per ha (d.b.h. at least 7 cm overbark). The fifth group, contains 2 variables (columns) for cumulative production: a) cumulative basal area per ha, which is the sum of the main crop basal area and the basal area of the present and previous thinnings; b) cumulative volume per ha, which is the sum volume per ha of the main crop and all present and previous thinnings. Finally, the sixth group in the yield models includes 1 variable (column), the mean annual increment (MAI).

The yield models for a yield class have been derived from a master table for each species using an appropriate top height/age relationship irrespective of the yield class (rate of growth). Therefore, they do not always describe accurately growth of individual stands. However, they do reflect the differences between different regimes. Thus, their use in the framework of this investigation is rather well justified. In 1980, work began on modelling diameter distributions which takes into consideration rates of changes of growth and competition. This will lead to a more accurate method in predicting yields, but until this research will have fully developed, the present yield models are urged to be used.

The present tabular format of yield models provides the type of information described in previous paragraphs, at discrete time points. That is, all variables correspond to ages, which are all multiples of 5 years. Since FORM_CFGENS requires functional relationships, so as continuous volume data be generated, some way of processing yield models had to be applied. An additional difficulty was created with respect to the storage requirement of all yield models for all spacings and regimes. The following approach has allowed to deal with these difficulties.

First, yield models of all major species met in British forests have been considered, but only certain spacings and thinning regimes have been included. Selection was forest specific. Information on tree spacing is not recorded in the typical

Forestry Commission subcompartment data files. However, forest managers are usually able to provide this information, before the solution process starts, empirically. For the Queen Elizabeth Forest Park, which has served as the study area in this project, one spacing has been used conventionally for each species group (personal communication with the forest manager). The species groups and their abbreviation codes as used by the Forestry Commission, as well as, the spacing for this forest, included in the timber volume data base at present are the following:

1. Sitka Spruce (SS) and Sitka Spruce all origins (WSS,QSS), spacing 1.7m
2. Norway Spruce (NS), Omorika Spruce (OMS), Other Spruces (XS), Mixed Conifers (MC), spacing 1.5m
3. Scots Pine (SP), Weymouth Pine (WEP), Other Pines (XP), spacing 1.4m
4. Corsican Pine (CP), Austrian Pine (AUP), Mountain Pine (MOP), Bishop Pine (BIP), Monterey Pine (RAP), Ponderosa Pine (PDP), spacing 1.4m
5. Lodgepole Pine (LP), Maritime Pine (MAP), Lodgepole Pine South Coastal (SLP), spacing 1.5m
6. Japanese Larch (JL), Hybrid Larch (HL), spacing 1.7m
7. Douglas Fir (DF), spacing 1.7m
8. European Larch (EL), spacing 1.7m
9. Western Hemlock (WH), spacing 1.5m
10. Red Cedar (RC), Lawson's Cypress (LC), Leyland Cypress (LEC), Japanese Cedar (JCR), spacing 1.5m
11. Grand Fir (GF), Coast Redwood (RSQ), Wellingtonia (WSQ), spacing 1.8m
12. Noble Fir (NF), Silver Fir (ESF), Other Firs (XF), spacing 1.5m
13. Oak (OK), Pedunculate Oak (POK), Sessile Oak (SOK), spacing 1.2m
14. Beech (BE), Red Oak (ROC), Sweet Chestnut (SC), Lime (LI), Common Lime (CLI), Elm (EM), English Elm (EEM), Wych Elm (WEM), Smooth-leaved Elm (SEM), Hornbeam (HBM), spacing 1.2m
15. Sycamore (SY), Norway Maple (NOM), Ash (AH), Birch (BI), Horse Chestnut (HCH), Alder (AR), Common Alder (CAR), Grey Alder (GAR), Other Broadleaves (XB), Mixed Broadleaves (MB), spacing 1.5m
16. Nothofagus Obliqua (OBN), Nothofagus procera (PRN), spacing 1.7m

Grouping has been made on the basis of the yield model used for volume estimations. That is, all species in each group assume use of the same yield model.

Second, a computer program was written in FORTRAN 77 (FORM_YPROGS) to extract and write in different files age/standing volume and age/thinning volume data from the yield models of each group. Felling volume data are obtained by adding the standing volume and the thinning volume at the age of felling. These data then were processed through CURVEFIT program and polynomials of degree eight were curve-fitted for each yield class and each species. The degree of the polynomial functions was established by trial on the basis of the standard deviation from the yield models. The smallest standard deviation was the most desirable. CURVEFIT program runs on EMAS (Edinburgh Multi-Access System) mainframe IBM 370-XA computer and computes coefficients for least squares approximation to data.

The thinning regimes presently included in FORM involve marginal thinning, marginal thinning with age of first thinning delayed by 5 years and marginal thinning with age of first thinning delayed by 10 years, all of intermediate type. The type of thinning is generally defined by an indicator, which is the ratio of the mean volume of thinnings (v) to the mean volume of stand after thinning (V). This ratio (v/V) for the intermediate type is about 0.8. Intermediate thinning is the commonest type of selective thinning in British forests. Other types involve low thinning (v/V = 0.6), line thinning (v/V = 1.0) and crown thinning (v/V = 1.2), but these are less common and have been excluded. However, the structure of FORM allows for these types to be included too, in further extentions to the model.

FORM_YPROGS also stores the regimes (alternative management strategies, see chapter 6) in a file called REGIME, which is read by many programs of FORM, in the coded format shown in Table 2 (pages 35 to 37). This Table shows the coded format of the marginal thinning regime with age of first thinning delayed by 10 years. The coded formats for the other regimes are shown in Appendix 1.

The first row includes the total number of species groups, which is the same for all regimes, that is 16. The second row includes the number of species in each group and the total number of yield classes for each species group. The third row contains the species list of each group (coded names).

The time span considered in this format is 100 years written in 10 columns with 10 digits each. Each digit reflects 1 time unit, that is 1 year. 5 numbers have been used to code activities. 0 indicates no silvicultural activity, 1 indicates year of thinning, 2 the year of felling, 3 the year of maximum mean annual increment and 4 is used when 2 and 3 coincide. A 100 years time span is a limited period for alternative

Table 2. Coded format for timber production timing under the delayed by 10 years thinning regime

```
16
 3 10
SS WSS QSS
 6  0000000000 0000000000 0000000000 0000000000 0010000100 0010000100 0000020000 0030000000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0000000010 0001000010 0001000000 0200000030 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000000 0000010000 1000010000 1000010000 4000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 0001000010 0001000010 0001000200 0003000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0100001000 0100001000 0002003000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 1000010000 1000010000 2000030000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000001 0000100001 0000000200 0000300000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000010 0001000010 0000020000 0003000000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000000100 0010000100 0000200000 0030000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000000100 0010000100 0002000300 0000000000 0000000000 0000000000 0000000000 0000000000
 4  9
NS OMS  XS  MC
 6  0000000000 0000000000 0000000000 0000000000 0000100000 1000010000 1000010000 1000020000 0000030000 0000000000
 8  0000000000 0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 0200000000 0000030000 0000000000
10  0000000000 0000000000 0000000000 0000000100 0010000100 0010000100 0010000002 0000000300 0000000000 0000000000
12  0000000000 0000000000 0000000000 0000010000 1000010000 1000010000 0002000000 0000000000 3000000000 0000000000
14  0000000000 0000000000 0000000000 0001000010 0001000010 0001000020 0000000000 0003000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 0010000100 0010000100 0000200000 0000000300 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000000 0100001000 0100001000 0020000000 0000000000 0300000000 0000000000 0000000000
20  0000000000 0000000000 0000000000 1000010000 1000010000 0200000000 0000030000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000000001 0000100001 0000100000 2000000000 0000300000 0000000000 0000000000 0000000000
 3  6
SP WEP  XP
 4  0000000000 0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100000 0200000000 0000000003
 6  0000000000 0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0020000000 0000000300 0000000000
 8  0000000000 0000000000 0000000000 0000000010 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000
10  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000020000 0000000003 0000000000 0000000000
12  0000000000 0000000000 0000000000 0010000100 0010000100 0010000002 0000000000 0030000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 1000010000 1000010000 1000020000 0000000000 3000000000 0000000000 0000000000
 6  8
CP AUP MOP BIP RAP PDP
 6  0000000000 0000000000 0000000000 0000000000 0010000000 1000010000 1000020000 3000000000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0000000100 0001000010 0001000000 0200000000 0003000000 0000000000 0000000000
10  0000000000 0000000000 0000000000 0000100001 0000100001 0000100000 0200300000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 0010000100 0010000100 0010000020 0030000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 1000010000 1000010000 1000230000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000001 0000100001 0000100000 0200000003 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000010 0001000010 0001000020 0000000030 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000100 0010000100 0010000200 0000000300 0000000000 0000000000 0000000000 0000000000
 3  6
LP MAP SLP
 4  0000000000 0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000200003 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0000000000 1000010000 1000010000 1000000200 0000030000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0000010000 1000010000 1000010000 0200000000 0000030000 0000000000 0000000000
10  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0200000300 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 1000010000 1000010000 1000002000 0000030000 0000000000 0000000000 0000000000
```

(Continued)

```
14  0000000000 0000000000 0000000010 0001000010 0001000000 0200000030 0000000000 0000000000 0000000000 0000000000
 2  6
JL  HL
 4  0000000000 0000000000 0000000000 0000010000 0001000010 0001000000 2003000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0100000100 0010000100 0000020300 0000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0000000010 0001000010 0001000010 0003020000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000001000 0100001000 0100001000 0320000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000100001 0000100001 0000100023 0000000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0001000010 0001000010 0003020000 0000000000 0000000000 0000000000 0000000000 0000000000
 1  9
DF
 8  0000000000 0000000000 0000000000 0000000100 0010000100 0010000100 0002000300 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000000 0000100001 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 0010000100 0010000100 0000200000 0030000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 1000010000 1000010002 0000000000 3000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000010 0001000010 0001000020 0000000030 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000100 0010000100 0010002000 0000000300 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000001000 0100001000 0100020000 0000003000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000001000 0100001000 0100020000 0000003000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000010000 1000010000 1000200000 3000000000 0000000000 0000000000 0000000000 0000000000
 1  5
EL
 4  0000000000 0000000000 0000000000 0000001000 0100001000 0100000002 0300000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000000000 1000010000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0000001000 0100001000 0100001000 0002003000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000100001 0000100001 0000100023 0000000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0010000100 0010000100 0000200300 0000000000 0000000000 0000000000 0000000000 0000000000
 1  7
WH
12  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0000020000 0000000300 0000000000 0000000000
14  0000000000 0000000000 0000000000 1000010000 1000010000 1000010002 0000000000 0000030000 0000000000 0000000000
16  0000000000 0000000000 0000000010 0001000010 0001000010 0000200000 0000000000 0003000000 0000000000 0000000000
18  0000000000 0000000000 0000001000 0100001000 0100001000 0200000000 0000003000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000010000 1000010000 1000000200 0000000000 3000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000100001 0000100001 0000002000 0000000003 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0001000010 0001000010 0000020000 0003000000 0000000000 0000000000 0000000000 0000000000
 4  7
RC  LC LEC JCR
12  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000020000 0000300000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0020000000 0030000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 1000010000 1000010000 1000010002 0000000000 3000000000 0000000000 0000000000
18  0000000000 0000000000 0000000010 0001000010 0001000010 0000002000 0000000030 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000100 0010000100 0010000100 0002000000 0030000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000001000 0100001000 0100001000 2000000000 0300000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000010000 1000010000 1000000200 0000000000 3000000000 0000000000 0000000000 0000000000
 3 10
GF RSQ WSQ
12  0000000000 0000000000 0000000000 0100001000 0100001000 0100002000 0300000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000001 0000100001 0000100001 0002000003 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000010 0001000010 0001000000 2000000030 0000000000 0000000000 0000000000 0000000000
```

(Continued)

```
18  0000000000 0000000000 0000000100 0010000100 0010000020 0000000300 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000001000 0100001000 0100002000 0000003000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000010000 1000010000 1000002000 0000030000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000010000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000 0000000000
26  0000000000 0000000000 0000100001 0000100001 0000020003 0000000000 0000000000 0000000000 0000000000 0000000000
28  0000000000 0000000000 0000100001 0000100001 0000200003 0000000000 0000000000 0000000000 0000000000 0000000000
30  0000000000 0000000000 0001000010 0001000010 0000200030 0000000000 0000000000 0000000000 0000000000 0000000000
 3  7
NF ESF  XF
10  0000000000 0000000000 0000000000 0000000010 0001000010 0001000010 0020000000 0000000030 0000000000 0000000000
12  0000000000 0000000000 0000000000 0000010000 1000010000 1000010000 0002000000 0000000000 3000000000 0000000000
14  0000000000 0000000000 0000000000 0001000010 0001000010 0001000010 0020000000 0003000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 0100001000 0100001000 0100000020 0000000000 0300000000 0000000000 0000000000
18  0000000000 0000000000 0000000001 0000100001 0000100001 0000020000 0000000003 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000100 0010000100 0010000100 0020000000 0000000300 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000001000 0100001000 0100001000 2000000000 0000003000 0000000000 0000000000 0000000000
 3  3
OK POK SOK
 4  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000000003
 6  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100002 0000000000 0000300000 0000000000
 8  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000200000 0000300000 0000000000 0000000000
12  4
BE ROC  SC  LI CLI SLI LLI  EM EEM WEM SEM HBM
 4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000
 6  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000
 8  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000300000
10  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000200000 0000300000 0000000000
10  4
SY NOM  AH  BI HCH  AR CAR GAR  XB  MB
 4  0000000000 0000000000 0000000001 0000100001 0000200000 0000300000 0000000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000100001 0000100001 0000400000 0000000000 0000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000001 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000
 2  5
OBN PRN
10  0000000000 0000000000 0000000100 0010000100 0020000300 0000000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000010000 1000020000 3000000000 0000000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0001000020 0003000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0010000400 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0100004000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
```

Key Note: Each value represents one time unit (i.e. 1 year).
0 = no activity, 1 = year of thinning, 2 = year of felling,
3 = year of maximum mean annual increment, 4 = when 2 and 3 coincide.

regimes with extended rotations by more than 15 years beyond the optimum felling age, especially for most of the broadleaved species. However, it was adopted because it was considered dangerous to extrapolate yield models beyond the 100th year of a stand age, as no real data are available to support any hypothesis. Thus, only three alternative regimes with extended rotations have been considered in the present form of FORM, that is extended rotations by 5, 10 and 15 years beyond the optimum felling age. Finally, all volume coefficients of the polynomial functions for each regime were stored in the CURVES volume data file, which can be read by the FORM_CFGENS program.

3.3 FOREST DISPERSED RECREATION

Forest dispersed recreation production functions are difficult to formulate, in contrast to timber production, because forest resource-oriented recreation is not an economic activity in the strict sense of the term. The output produced, which is eventually the level of enjoyment attained by recreationists, is very difficult to cost by direct economic methods. Also the factors determining recreational use of forest land and value of product (recreational experience) are very complex and variable.

Most of the studies in the recreation research field have dealt either with recreation demand from the economic view point (see chapter 2), or measurement of resource recreational use of specific sites or provision of recreational opportunity (La Page, 1962; Lucas, 1963; Wagar, 1964; James and Rich, 1966; Mutch, 1968; Schreuder, 1970; Hecock, 1970; Hamill, 1971; Tivy, 1973; Brotherton, 1973; Grayson, Sidaway and Thompson, 1973; Schreuder, Tyre and James, 1975; Clark and Stankey, 1979; Mercer, 1981; Tivy, 1980; Johnstone and Tivy, 1980; Koch, 1984; Sieränen, 1984; Collin and Hodge, 1984).

However, multi-objective models, like FORM require functional relationships, which would relate forest resource attributes and visitor days or some recreation resource suitability index. A search in the literature did not reveal work of this type which could be used in FORM, with the exception the work of Goodall (1975), Goodall and Whittow (1975) and Hockin, Goodall and Whittow, (1977). They produced a simple mathematical model, which relates forest development stages (pre-thicket, thicket, semi-mature, and mature) to an index (P_r) of recreational potential. However, this model was very difficult to use within the FORM structure, which is based on the subcompartment data file parameters. The TRIP information system (recreation package) developed in 1973 (TRRU, 1974) with its STAR series for woodlands (TRRU,1978), was a possibility that has also been considered to use in FORM, but the information generated from the package is suitable for regional recreation planning and management rather than forest-level management. Therefore, it was necessary to develop a model, which related recreational potential with the forest descriptors, used in the subcompartment data file. The following paragraphs of this section describe the development of dispersed recreation statistical models, which can be used in multi-objective forest management modelling.

Method

Data were collected through a survey carried out in the Queen Elizabeth Forest Park between the 28th of July and 17th of August 1986. The survey included direct interviews of visitors at specific sites selected throughout the forest. Since recreation descriptors were sought to relate with physical characteristics of forests on a subcompartment basis, random stratified sampling was originally considered as a more comprehensive approach of collecting data. However, time constraints and necessity to curtail survey costs led to rejection of this approach. The following method was finally adopted.

5 parking sites were chosen in each of the three forest blocks of the Park, making a total of 15 for the whole forest. Parking places were thought of being suitable as sampling points, because most forest visitors reach forests by car and therefore these places can be viewed as starting and terminal points for forest dispersed recreationists and water-based recreationists (see next section).

A scheme involving circular travel around the set of different sampling sites allowed for data recording at different times of day, days of week and weather conditions. The survey was made one week in each forest block, between 11.00 a.m and 6 p.m. on a one-hour basis in each site allowing half an hour for travelling between sites.

All people found on and coming to the site were interviewed (one questionnaire per group). Each interview included a questionnaire along with a map, which covered the area around the sampling site to a radius of 60 miles. This figure was established, because it was felt that 60 miles is about the maximum that a day-visitor can be dispersed for his recreational activity.

Visitors were asked to indicate on the map the places they had visited when pursuing their recreational activities as well as the time they spent in the forest. The subcompartments visited were identified from the survey maps, which were drawn on a scale of 1:10,560 based on the stock maps of the same scale. The subcompartment data base then was used to extract all forest descriptors related to those subcompartments. Each subcompartment identified one case. Sampling sites were selected in such a way, so that visitors would have access to different habitat types (see chapter 6 for a detailed discussion on habitat types). The following four groups were considered as predictors.

A. Time variables:
-Day of Week (qualitative)
-Time of Day (qualitative)

B. Weather variables
-Weather (qualitative)

C. Mobility variables
-Transport Means (qualitative)
-Travelling Distance (quantitative)
-Distance from Residence (quantitative)

D. Forest variables
-Age of Trees (quantitative)
-Altitude (quantitative)
-Ground Conditions (qualitative)
-Ground Roughness (qualitative)
-Slope (qualitative)
-Habitat Type (qualitative)

Time variables are both qualitative coded as 1 and 0. For Day of Week (DAY), 1 stands for 'working day', that is from Monday to Thursday and 0 for 'weekend', including Friday, Saturday and Sunday. For Time of Day (TIME), 1 denotes 'mornings', including morning hours and two hours after noon, while 0 is used for 'afternoons', that is all hours between 2.0 and 6.0 o'clock in the afternoon.

The Weather variable (WEATHER) is also qualitative coded as 1 for 'good' weather and 0 for 'poor' weather. 'Poor Weather' in the context of this survey is characterized as rainy,cold and very windy, that is these weather conditions which usually do not permit outdoor recreational activities. Any other description refers to 'Good Weather'.

From the mobility variables, the Transport Means (TRAN) is qualitative, coded as 1 for motor transport, that is cars, cars/caravans, dormobiles, minibuses, motorcycles, buses or trains and 0 for 'on foot' and 'bicycle' access. Travelling Distance (TRAVD) and Distance from Residence (RESID) are quantitative, measured in kilometres distance from the sampling site.

From the forest variables, Age of Trees (AGE) is measured in years, that is in number of growing seasons, that have elapsed since the stand was planted and Altitude (ALT) is measured in metres above sea level at Newlyn. Ground Conditions (GRC), Ground Roughness (GRR) and Slope (SL) are classified according to Forestry Commission terrain classification, as it is used in the subcompartment data file (Rowan, 1977). Aggregation, however, was applied to the last three forest variables in order to reduce the number of qualitative variables in the final recreation model. In the Forestry Commission's classification scheme a scale from 1 to 5 is used to characterize each of the above variables.

For Ground Conditions, 1 stands for 'very good', 2 for 'good', 3 for 'average', 4 for 'poor' and 5 for 'very poor'. In the recreation model 1, 2 and 3 were coded as 1 describing generally good ground conditions for recreational activities, and 4 and 5 as 0, describing poor ground conditions.

For Ground Roughness, 1 describes 'very even' ground, 2 'slightly uneven', 3 'uneven', 4 'rough', and 5 'very rough'. The first three classes were also coded as 1 for generally 'even' ground and 0 for 'rough'.

Finally, for the Slope variable, 1 stands for 'level', 2 for 'gentle', 3 for 'moderate', 4 for 'steep' and 5 for 'very steep'. Again, 1 was used for the first three classes describing 'gentle' slopes and 0 for the last two, describing 'steep' slopes.

Habitat Type is a categorical variable. Three broad types were distinguished and resulted in three models. The first model refers to a fully stocked forest habitat (HT). The second model relates to overmature growth forest habitats (OMG), which include all old trees left unharvested beyond their optimum felling ages. The third model refers to other type land habitats (OTH), which include open land with scattered trees or groups of trees, grassland, moorland and heatherland.

In the first model, the Habitat Type variable was further distinguished in four types on the basis of mixture of dominant species in the overstorey. 1 was used to code spruce stands, 2 spruce/pine/larch stands, 3 mixed conifer stands and 4 conifer/brodleaf stands. Since Habitat Type is a categorical variable, the total number required in the model is one less than the number of categories. That is in the fully stocked forest recreation model this variable is described as follows:

$HT_{1i} = 1$, if habitat type is spruces

$HT_{1i} = 0$, otherwise

$HT_{2i} = 1$, if habitat type is spruce/pines/larches

$HT_{2i} = 0$, otherwise

$HT_{3i} = 1$, if habitat type is mixed conifers

$HT_{3i} = 0$, otherwise

These three variables taken together represent the four groups. For spruce habitat type $HT_1 = 1$, $HT_2 = 0$, $HT_3 = 0$, for spruce/pine/larch habitat $HT_1 = 0$, $HT_2 = 1$, $HT_3 = 0$, for mixed conifers $HT_1 = 0$, $HT_2 = 0$, $HT_3 = 1$ and for conifers/broadleaves $HT_1 = 0$, $HT_2 = 0$, $HT_3 = 0$. Clearly, only one dummy variable is required for all other qualitative regressors in the models, since they have been chosen so as to represent only two categories each.

Results/Discussion

Multiple linear regression analysis was performed to derive the three recreation models. The logarithm of visitor days was the dependent variable in all three models. The logarithm was taken to achieve linearity, after examining scatter plots of the visitor days variable against all regressors, which showed violations of the linearity assumption of the regression analysis. Because of the large number of categorical variables examined in the models, it was not feasible to incorporate interaction terms.

Pearson's correlation coefficient was used as a criterion for the variables to be retained in the model. Variables with a correlation coefficient greater than 0.6 were dropped. The highest intercorrelation between the remaining regressors was 0.55, so that multicollinearity was not a problem.

Other model deficiencies in regression analysis can be detected by examining the residuals (Chatterjee and Price, 1977; Berry and Feldman, 1985; Schroeder, Sjoquist and Stephan, 1986). In general, the model is correct when the standardized residuals fall between 2 and -2 and are randomly distributed about zero. Also, if the bands which contain the residual plots are two lines parallel to the x-axis, there is no evidence of heteroscedasticity, that is the error variance is constant. Studentized residual plots were examined for all models and the above conditions were verified.

Table 3 shows the predictors of the model developed for recreation in fully stocked forests, using stepwise regression. Slope, Transport, Age of Trees and Habitat Type are the variables finally included. These have accounted for approximately 64 percent of the variance in logarithm of visitor days, which is the dependent variable.

$$(1.1) \quad \text{Log VD} = -2.599 + 0.637 *(\text{SL}) + 0.310 * (\text{TRAN}) - 0.0063 *(\text{AGE}) + 0.116*(\text{HT}_1) + 0.173 *(\text{HT}_2) + 0.287 *(\text{HT}_3)$$

where VD = Visitor days

SL = Slope

TRAN = Transport

AGE = Age of Trees

HT_1 = Spruces Habitat Type

HT_2 = Spruces/Pines/Larches Habitat Type

HT_3 = Mixed Conifers Habitat Type

The partial slope coefficients of the regression equation (B's) represent the change in the expected value of the dependent variable associated with a one unit increase in each independent variable, when all other independent variables in the model are held constant. This is usually so for quantitative regressors.

Table 3. Forest Dispersed Recreation Model: Fully Stocked Forest

Step	Variable	B	Beta	R	R^2
1	Slope	0.637	0.807	0.632	0.399
2	Transport	0.310	0.420	0.733	0.537
3	Age of Trees	-0.0063	-0.333	0.777	0.604
4	HT_3	0.287	0.374	0.788	0.622
5	HT_2	0.173	0.278	0.794	0.632
6	HT_1	0.116	0.134	0.798	0.637
	Constant	-2.599			

N = 123, $F(6,116) = 42.511$, $P < 0.001$ (HT1: $P < 0.01$)

Table 4. Forest Dispersed Recreation Model: Overmature Growth Forest

Step	Variable	B	Beta	R	R^2
1	Slope	0.718	0.581	0.776	0.602
2	Transport	0.332	0.259	0.859	0.688
3	OMH	-0.279	-0.213	0.844	0.712
	Constant	-2.691			

N = 209, $F(4,205) = 97.49$, $P < 0.001$

For the categorical variables a somewhat different interpretation is attributed. By evaluating equation (1.1) for the different categorical variables, it follows that there is a different regression equation for each of the sixteen (4 habitat X 2 slope X 2 transport) categories:

Equations (1.2)

HAB.TYPE	SLOPE	TRAN.	REGRESSION EQUATION
1. HT1	1	1	LogVD=(-2.599+0.637+0.310+0.116) -0.0063*(AGE)
2. HT1	0	1	LogVD=(-2.599+0.310+O.116)-0.0063*(AGE)
3. HT1	1	0	LogVD=(-2.599+0.637+0.116)-0.0063*(AGE)
4. HT1	0	1	LogVD=(-2.599+0.116)-0.0063*(AGE)
5. HT2	1	1	LogVD=(-2.599+0.637+0.310+0.173) -0.0063*(AGE)
6. HT2	0	1	LogVD=(-2.599+0.310+0.173)-0.0063*(AGE)
7. HT2	1	0	LogVD=(-2.599+0.637+0.173)-0.0063*(AGE)
8. HT2	0	0	LogVD=(-2.599+0.173)-0.0063*(AGE)
9. HT3	1	1	LogVD=(-2.599+0.637+0.310+0.287) -0.0063*(AGE)
10. HT3	0	1	LogVD=(-2.599+0.310+0.287)-0.0063*(AGE)
11. HT3	1	0	LogVD=(-2.599+0.637+0.287)-0.0063*(AGE)
12. HT3	0	0	LogVD=(-2.599+0.287)-0.0063*(AGE)
13. HT4	1	1	LogVD=(-2.599+0.637+0.310)-0.0063*(AGE)
14. HT4	0	1	LogVD=(-2.599+0.310)-0.0063*(AGE)
15. HT4	1	0	LogVD=(-2.599+0.637)-0.0063*(AGE)
16. HT4	0	0	LogVD=-2.599-0.0063*(AGE)

According to this model, the categorical variables help to determine the visitor days for each habitat type as a function of slope and transport categories after adjustment for the age of the forest stand.

The coefficient of Age of Trees is -0.0063. That is each additional year of tree growth is estimated to be worth a decrease of logarithm of visitor days by 0.0063. This seemed rather incompatible with what was expected. Most of scenic beauty models presented in the literature (Arthur, 1977; Schroeder and Daniel, 1981; Buhyoff, Hull IV, Lien and Cordell, 1986) have shown a positive correlation between Age of Trees and Scenic Beauty estimator. However, recreation is substantially different from scenic beauty. A recreation site, for example, may be judged as moderately beautiful by common people, but it may be suitable for a number of recreational activities. Therefore, it may be preferred more than some other site, which is aesthetically more pleasant, but it is less suitable for these recreational activities.

On the other hand, only trees aged between 10 and 60 years , the average age being 33 years, have been included in this model. For fastgrowing conifers, for example, the difference in appearance between trees 30 years old and 40 years old is rather subtle. Also design factors were not considered in any of these models. Design considerations in Forestry Commission plantations began only in early 70's. Therefore, younger plantations are likely to be more attractive than older ones, at this stage of development.

Looking at the Beta coefficients, another interpretative scenario would suggest that the negative sign of the Age of Trees variable is a result of the relatively higher importance of the other variables in the model. Beta coefficients (standardized regression coefficients) are based upon the standard deviations of the regressors' distributions. Therefore, they constitute a better measure of the importance of each variable, in contrast to the B coefficients, which depend on the unit of measurement of the regressors. Thus, Table 2 suggests that Slope and Transport Means are more important than Age of Trees for the recreation visitors. In other words, a recreational site with gentle slopes, easily accessed by car and young trees is likely to be more preferrable from a site with steep slopes and older trees. However, this scenario requires further investigation in order to be better substantiated.

The coefficients of the other variables can be interpreted from equations (1.2). The coefficient of the Slope variable is 0.637. This amount represents the average increment in visitor days (logarithm) associated with a slope category, that is gentle slopes are associated with more visitor days. The same holds for transport. Motor-transport is positively correlated to visitor days.

For the Habitat Type, the coefficient of HT_1 variable (0.116) measures the visitor days differential for the spruces habitat relative to the conifers/broadleaves. Similarly, 0.173 measures the differential in visitor days of the mixed conifers habitat relative to conifers/broadleaves. The difference (0.173-0.116) measures the differential in visitor days of the spruces habitat relative to spruces/pines/larches. (0.287-0.173) is the measure of the differential in visitor days of the spruces/pines/larches relative to mixed conifers, while the difference of the coefficients of the variables HT_3 and HT_1, that is (0.287-0.116) measures the differential in visitor days of the spruces habitat relative to mixed conifers.

Table 4 shows the predictors of the model developed for dispersed recreation in overmature growth stands, using stepwise regression. Slope, Transport Means and the overmature growth habitat are the variables included. The R^2 of 0.712 implies that 71.2 percent of the variance in logarithm of visitor days is accounted by these three variables. The prediction model can be written out as an equation:

$$\text{(2.1)} \quad \text{LogVD} = -2.691 + 0.718*(\text{SL}) + 0.332*(\text{TRAN}) - 0.279*(\text{OMH})$$

where, VD = visitor days
SL = Slope
TRAN = Transport
OMH = Overmature growth habitat

By evaluating equation (2.1) for the different values of the categorical variables, a different regression equation can be written out for each of the eight (2 habitat X 2 slope X 2 transport) categories:

Equations (2.2)

HAB. TYPE	SLOPE	TRAN.	REGRESSION EQUATION
1. OMH	1	1	LogVD=(-2.691+0.718+0.332-0.279)
2. OMH	0	1	Log VD=(-2.691+0.332-0.279)
3. OMH	1	0	Log VD=(-2.691+0.718-0.279)
4. OMH	0	0	Log VD=(-2.691-0.279)
5. OTHER	1	1	Log VD=(-2.691+0.718+0.332)
6. OTHER	0	1	Log VD=(-2.691+0.332)
7. OTHER	1	0	Log VD=(-2.691+0.718)
8. OTHER	0	0	Log VD=-2.691

The coefficient of Slope (0.718) represents the incremental amount in visitor days (logarithm) when slopes are gentle and the coefficient of Transport (0.332) the incremental amount in visitor days (logarithm) when motor-transport is used by the forest visitors.

The Habitat Type coefficient is the differential in visitor days (logarithm) of fully stocked forest environments and other land type habitats relative to overmature growth stands. A decrease is expected in visitor days when considering overmature stands relative to fully stocked stands or other land type habitats. The standardized regression coefficients (Beta) show that the Slope and Transport variables are more important than the overmature growth habitat variable.

Table 5 shows the predictors of the model developed for dispersed recreation in other land habitat type. Slope, Altitude, Transport and Other Land Habitat are the variables finally included in the model and have accounted for approximately 82 percent of the variance in the logarithm of visitor days ($R^2 = 0.816$).

Table 5. Forest Dispersed Recreation Model: Other Land Habitat

Step	Variable	B	Beta	R	R^2
1	Other Land	1.610	0.566	0.804	0.647
2	Slope	1.003	0.359	0.855	0.731
3	Altitude	-0.0052	-0.270	0.874	0.765
4	Transport	0.718	0.241	0.903	0.816
	Constant	-2.694			

N = 309, F(5,304) = 136.881, P < 0.0001

The regression equation is written out as follows:

(3.1) $$LogVD = -2.694+1.610*(OLH)+1.003*(SL)-0.0052*(AL) +0.718*(TRAN)$$

where, VD = Visitor Days
SL = Slope
TRAN = Transport
AL = Altitude
OLH = Other Land Habitat

By evaluating (3.1) for the different values of categorical variables a set of regression equations can be formed for each of the eight (2 habitat X 2 slope X 2 transport) categories:

Equations (3.2)

HAB. TYPE	SLOPE	TRAN.	REGRESSION EQUATION
1. OT. LAND	1	1	LogVD=(-2.694+1.610+1.003+0.718) -0.0052*(AL)
2. OT. LAND	0	1	Log VD=(-2.694+1.610-0.718)-0.0052*(AL)
3. OT. LAND	1	0	Log VD=(-2.694+1.610-1.003)-0.0052*(AL)
4. OT. LAND	0	0	Log VD=(-2.694-1.610)-0.0052*(AL)
5. OTHER	1	1	Log VD=(-2.694+1.003+0.718)-0.0052*(AL)
6. OTHER	0	1	Log VD=(-2.694+0.718)-0.0052*(AL)
7. OTHER	1	0	Log VD=(-2.694+1.003)-0.0052*(AL)
8. OTHER	0	0	Log VD=-2.694-0.0052*(AL)

According to this model visitor days are determined for other land habitat as a function of Slope and Transport categorical variables, after adjustment for the altitude of the forest stand. The coefficient of Altitude is -0.0052. This means that each additional metre of altitude is estimated to be worth a decrease of the logarithm of visitor days by 0.0052. The negative sign is compatible with before analysis expectations. The coefficients 1.003 and 0.718 can be interpreted as the incremental amount in visitor days (logarithm) associated with the Slope and Transport categories respectively. The coefficient 1.610 measures the differential in visitor days (logarithm) for the other land habitat relative to fully stocked forest habitats and overmature growth habitats. Not surprisingly the correlation is positive. Beta coefficients show that other land habitat variable is more important than slope, transport and altitude variables.

Analysis of variance in all models showed all regression coefficients to be significant. For the first model (equation (1.1)), P was less than 0.001 with the exception of the HT_1 variable, which was significant at $P < 0.01$. Statistically, this variable should have been dropped. From the interpretative view point, however, it had to be retained because it is a categorical variable. Regression coefficients for the second model (equation (2.1)) were significant at $P < 0.001$ and for the third model (equation (3.1)) at $P < 0.0001$.

Conclusion

The dispersed recreation visitor days prediction models presented in this section are subject to limitations. They are intended to be applied to forest environments similar to the forest environment of Queen Elizabeth Forest Park.

Formation of habitats was based on aggregation of stands consisted of a certain mixture of species. Most of the species met in British forests have been considered, thus making it easier to generalize. However, design considerations and unique physical features are not included in these models. These restrictions can be overcome with further model development efforts.

Predictions arising from these models are statistical estimates. Therefore deviations from predicted values are to be expected. Predictions should be interpreted as indicating a range of potential outcomes rather than as a single , precise prediction. Despite these limitations these models can be used to predict consequences of harvest management actions to similar to the Queen Elizabeth Forest Park environments. An attempt of this type is described in Chapter 7.

3.4 FOREST WATER-BASED RECREATION

Water features (lakes, streams, rivers) have been recognized by recreational planners as playing a major role in forest recreation (Douglass, 1975; Tivy, 1980; Johnstone and Tivy, 1980). For many forest recreationists water forms the main purpose for their visit as they go to forests to participate solely in water-based activities. In other cases, water supplements some of their other activities, or water enhances nearby land-based activities by improving the scenery. Forest stands, therefore, which contain water elements are expected to be used for recreational activities in different intensities from stands which do not. Also, the interaction of the recreationists who visit the forest water areas with the surrounding forest is expected to be different. In forestry practice, most of the retentions in terms of timber are being done in forest stands with water, because a larger inrush has been observed over the years in forest water areas.

The preceding reasoning led to the development of different models for forest water-based recreation.

Method

The data collection procedure has been the same as for the forest dispersed recreation models described in the previous section. The subcompartments with water visited by recreationists in the survey were separated to form a different data base. The same variables were also used as the intention was to relate visitor days to different forest habitats which in addition contain water.

Three models were developed for forest water-based recreation too on the basis of habitat type: 1) fully stocked forest stands containing water 2) overmature growth stands with water and 3) other land habitat type with water. In the first model, Habitat Type was coded as 1 for spruces forest stands with water, 2 for spruces/pines/larches stands with water and 3 for mixed conifer stands with water. The fourth sub-type, that is conifer/broadleaf stands has been excluded from the model because no data were available from the survey data collection procedure. For the fully stocked forest water-based recreation model, the Habitat type variable is represented as follows:

$HT_1 = 1$ if the Habitat Type is spruces with water

$HT_1 = 0$ otherwise

$HT_2 = 1$ if the Habitat Type is spruces/pines/larches with water

$HT_2 = 0$ otherwise

These two variables taken together reflect all three groups. For the spruces habitat with water $HT_1=1$, $HT_2=0$, $HT_3=0$. For the spruces/pines/larches habitat with water $HT_1=0$, $HT_2=1$, $HT_3=0$. For the mixed conifer habitat with water $HT_1=0$, $HT_2=0$, $HT_3=0$.

Results/Discussion

Multiple linear regression was performed again to derive the three forest water-based recreation models. Visitor days is the dependent variable, transformed in logarithic form to achieve linearity. As in the forest dispersed recreation models no interaction terms were included due to the large number of categorical variables. Only the variables with a Pearson's correlation coefficient less than 0.60 were retained. Multi-collinearity did not appear as a problem in the regressors finally included, as the highest intercorrelation was 0.54. Heteroscedasticity also was not a problem when the studentized residuals were examined. Residuals were randomly distributed about zero in the zone between +2 and -2.

Table 6 shows the predictors of the forest water-based recreation model of fully stocked stands in the stepwise regression fashion.

Table 6. Forest Water-based Recreation Model: Fully Stocked Forest

Step	Variable	B	Beta	R	R^2
1	Slope	0.010	0.302	0.559	0.312
2	Transport	0.497	0.648	0.637	0.406
3	Age of Trees	0.718	0.499	0.769	0.590
4	HT_2	0.202	0.346	0.835	0.697
5	HT_1	0.284	0.138	0.846	0.715
	Constant	-3.354			

$N = 229$, $F(6,223) = 102.426$, $P < 0.0001$

Age of Trees, Transport, Slope and Habitat Type (mixture of species) are the variables included. The R^2 of 0.715 indicates that 71.5 percent of the variance in the logarithm of visitor days is accounted by these variables. The equation in mathematical form can be presented as follows:

$$\text{LogVD} = -3.354+0.0010*(\text{AGE})+0.497*(\text{TRAN})+0.718*(\text{SL}) +0.284*(\text{HT}_1)+0.202*(\text{HT}_2) \quad (4.1)$$

where, VD = Visitor Days
AGE = Age of Trees
TRAN = Transport
SL = Slope
HT1 = Spruces habitat with water
HT2 = Spruces/Pines/Larches with water

By evaluating equation (4.1) for the different values of categorical variables, a different regression equation is derived for each of the 12 (3 habitat X 2 slope X 2 transport) categories:

Equations (4.2)

HAB. TYPE	SLOPE	TRAN.	REGRESSION EQUATION
1. HT1	1	1	Log VD=(-3.354+0.718+0.497+0.284)+ +0.010*(AGE)
2. HT1	0	1	Log VD=(-3.354+0.497+0.284)+0.010*(AGE)
3. HT1	1	0	Log VD=(-3.354+0.718+0.284)+0.010*(AGE)
4. HT1	0	0	Log VD=(-3.354+0.284)+0.010*(AGE)
5. HT2	1	1	Log VD=(-3.354+0.718+0.497+0.202)+ +0.010*(AGE)
6. HT2	0	1	Log VD=(-3.354+0.497+0.202)+0.010*(AGE)
7. HT2	1	0	Log VD=(-3.354+0.718+0.202)+0.010*(AGE)
8. HT2	0	0	Log VD=(-3.354+0.202)+0.010*(AGE)
9. HT3	1	1	Log VD=(-3.354+0.718+0.497)+0.010*(AGE)
10. HT3	0	1	LogVD=(-3.354+0.497)+0.010*(AGE)
11. HT3	1	0	LogVD=(-3.354+0.718)+0.010*(AGE)
12. HT3	0	0	LogVD=-3.354+0.010*(AGE)

The visitor days for each habitat type are determined as a function of slope and transport variables after adjustment for the age of the forest stand.

The coefficient of the AGE variable is 0.010. That is, each additional year of tree growth would result in an increase of the logarithm of visitor days for the specific stand under evaluation of 0.010. This is compatible with what was expected, but contrasts with the negative coefficient of the AGE variable in the relevant forest dispersed recreation model presented in the previous section. This may be explained by the fact that the average age of trees included in the sample was 50, while in the relevant dispersed recreation model it was 33. The range of age of trees, however, was the same in both models, that is only trees aged between 10 and 60 years were included in the data base.

The coefficients of Slope and Transport (0.718 and 0.497 respectively) indicate that the average increment in the logarithm of visitor days associated with a slope or transport category would be 0.718 and 0.497 respectively.

For the Habitat Type variable, the coefficient of HT_1 (0.284) measures the visitor days differential for the spruces habitat type relative to mixed conifers, while the coefficient of HT_2 (0.202) the visitor days differential for the spruces/pines/larches relative to mixed conifers. The difference (0.284-0.202) is interpreted as the differential in visitor days of the spruces/pines/larches relative to spruces.

Table 7 shows the predictors of the model developed for water-based recreation in overmature growth forest stands with stepwise regression. 62.5 percent of the variance in the dependent variable is accounted by the three categorical variables included in the model, that is Slope, Transport and Overmature growth habitat type.

Table 7. Forest Water-based Recreation Model: Overmature Growth Forest

Step	Variable	B	Beta	R	R^2
1	Transport	0.644	0.987	0.652	0.425
2	Slope	0.901	0.557	0.790	0.624
3	OMH	-0.184	-0.273	0.808	0.652
	Constant	-3.205			

N = 335 F(4,331) = 168.572 P < 0.0001

The equation representing the model is as following:

(5.1) $$\text{Log VD} = -3.205+0.644*(\text{TRAN})+0.901*(\text{SL})-0.184*(\text{OMH})$$

where, VD = Visitor Days
TRAN = Transport
SL = Slope
OMH = Overmature growth habitat with water

By evaluating equation (5.1) for the different values of the categorical variables the following 8 (2 habitat X 2 slope X 2 transport) regression equations can be written out:

Equations (5.2)

HAB. TYPE	SLOPE	TRAN.	REGRESSION EQUATION
1. OMH	1	1	Log VD=(-3.205+0.901+0.644-0.184)
2. OMH	0	1	Log VD=(-3.205+0.644-0.184)
3. OMH	1	0	Log VD=(-3.205+0.901-0.184)
4. OMH	0	0	Log VD=(-3.205-0.184)
5. OTHER	1	1	Log VD=(-3.205+0.901+0.644)
6. OTHER	0	1	Log VD=(-3.205+0.644)
7. OTHER	1	0	Log VD=(-3.205+0.901)
8. OTHER	0	0	Log VD=-3.205

Note that all 8 regression equations are equal to some constant value, since no quantitative variables are included in the equation (5.1). The same was true for the relevant dispersed recreation model. The values 0.644 and 0.901 indicate the incremental amount in visitor days (logarithm) for the slope and transport categories. The sign of the Habitat Type variable is negative. It implies a decrease in visitor days when considering overmature growth stands with water relative to fully stocked ones and other land habitats with water.

Table 8 contains the descriptors of the model developed for recreation in other land type habitat with water. 65 percent approximately of the variance in the dependent variable is attributed by the slope, transport and habitat type finally included in the model.

Table 8. Forest Water-based Recreation Model: Other Land Habitat

Step	Variable	B	Beta	R	R^2
1	Other Land	0.666	0.552	0.639	0.409
2	Transport	0.553	0.494	0.796	0.633
3	Slope	0.716	0.124	0.805	0.648
	Constant	-3.056			

$N = 1067$, $F(4,1063) = 680.563$, $P < 0.0001$

The following equation is derived from Table 8:

(6.1) $$\text{Log VD} = -3.056+0.666*(\text{OTH})+0.553*(\text{TRAN})+0.716*(\text{SL})$$

where, VD = Visitor Days
OTH = Other land habitat type
TRAN = Transport
SL = Slope

Analytically the 8 equations emanating from equation (6.1) after evaluation of the three categorical variables are written out as following:

Equations (6.2)

HAB. TYPE	SLOPE	TRAN.	REGRESSION EQUATION
1. OT. LAND	1	1	LogVD=(-3.056+0.716+0.553+0.666)
2. OT. LAND	0	1	Log VD=(-3.056+0.553+0.666)
3. OT. LAND	1	0	Log VD=(-3.056+0.716+0.666)
4. OT. LAND	0	0	Log VD=(-3.056+0.666)
5. OTHER	1	1	Log VD=(-3.056+0.716+0.553)
6. OTHER	0	1	Log VD=(-3.056+0.553)
7. OTHER	1	0	Log VD=(-3.056+0.716)
8. OTHER	0	0	Log VD=-3.056

Again each of the (6.2) regression equations is represented by a constant term because equation (6.1) consisted only of categorical variables.

The logarithm of visitor days is expected to increase by 0.553 and 0.716 for each of the slope and transport categories respectively. The coefficient of the Habitat Type is 0.666 and implies that an increase is expected in the dependent variable by 0.666 relative to fully stocked and overmature growth stands which also contain water. This habitat type in both dispersed and water-based forest recreation appeared more preferable in relation to fully stocked and overmature growth stands. This was expected in this country considering the public debate about afforestation in the uplands of Scotland (Countryside Commission for Scotland, 1986).

By examining the Beta coefficients it appears that in the first two models (5.1) and (6.1) transport is of highest importance in terms of relative sensitivity of the prediction equation to changes in this variable. In model (6.1) the Habitat Type variable has the highest Beta coefficient.

Analysis of variance in all three water-based recreation models revealed that all regression coefficients are significant with $P < 0.0001$.

Conclusions

Some useful observations can be drawn about forest water-based recreation relative to forest dispersed recreation input-output relationships.

The Age of Trees is negatively correlated to Visitor Days (logarithm) in the fully stocked forest dispersed recreation model, implying that other descriptors, such as the Slope and the Mixture of species are more important. Indeed, mixed conifer stands appear more preferable than pure spruces stands.

On the contrary, the Age of Trees is positively correlated to Visitor Days (logarithm) in the fully stocked water-based recreation model, while Mixture of species is less important. Pure spruce stands appear more preferrable than spruce/pine/larch stands in forest water areas. This probably suggests that the most attractive element to forest water-based recreationists is the water, rather than the trees or mixture of tree species, although trees do enhance the recreation activity by improving the scenery (positive correlation).

The other two recreation models for overmature growth stands and other land habitat appear more compatible. In both cases the other land habitat was shown as being more preferred relative to fully stocked stands or overmature growth stands.

The same limitations discussed in the previous section apply also to the forest water-based recreation models. Generalization should only be attempted to environments similar to that of the Queeen Elizabeth Forest Park. Design factors and uniqueness were not considered. Predictions are subject to deviations since the models are only statistical estimates. These models, like the dispersed recreation ones can be used to predict consequences of harvest management regimes (see Chapter 7) as well as help managers and planners when developing recreation plans.

3.5 RED DEER STALKING

Deer stalking is an important recreational opportunity of forestry plantations. König and Gossow (1979), reported that even-aged forest plantations have higher capacities than natural forests, because they contain larger number of trees in the age classes favourable for deer.

Deer provide attractive sport, enhance the aesthetic quality of forest environment and provide good quality meat. The most important deer species from the game management point of view are red and roe deer. This section is only dealing with red deer. The reason for this is that a number of rather well documented studies on red deer ecology and management in Scottish conditions made it possible to compile a computer-based algorithm, suitable for FORM, which allows within limits forecast of red deer sporting value.

Red deer have established themselves in forest plantations because their demands for energy and nutritional requirements are well satisfied, while also they benefit from the enhanced shelter forest environment offers (Dzieciolowski, 1970; König and Gossow, 1979; Phillips and Mutch, 1974; Mutch, Lockie and Cooper, 1976; Ratcliffe, 1984; Ratcliffe, 1987). Mitchell, Staines and Welsh, (1977), Cooper and Mutch (1979) and Ratcliffe (1984,1987) reported densities of red deer in Scottish woodlands in the range of 5-15 per square kilometre, almost identical to the densities found in open-range habitats. The same authors also stressed the necessity of adoption of management schemes based on good scientific information, which would permit reconciliation of deer interests and forestry. Conflict arises from the considerable damage that deer usually inflict upon commercial forestry, mainly by destroying seedlings, checking tree growth by heavy browsing and bark stripping.

Forecast of deer sporting value is a very difficult task as it requires much information on population dynamics, density and habitat preferences. In addition to this timber management causes changes in the proportions of forest successional stages both in space and time, thus altering the ability of a specific habitat to support changing densities of deer through time (Ratcliffe, Hall and Allen, 1986). Standard criteria with which to determine the amount of deer to be shot in the interest of forest conservation have not been established as yet. To fix such criteria on a nation-wide scale is almost impossible because of very specific local differences in forest and game management. The following algorithm has been compiled for the Queen Elizabeth Forest Park within the frame of FORM. Generalization could be attempted with caution.

The algorithm

The basic sources which provided information for the compilation of this algorithm are: the subcompartment data base, the work of Staines and Welch (1984) on deer habitat preference, the work of Cooper and Mutch (1979) on management of red deer in plantations, Ratcliffe's study (1987) on management of red deer in upland forests, published as Forestry Commission Bulletin No.71 and finally personal communication with the Queen Elizabeth Forest Park staff.

Habitat types have been used in the same context as in the recreation sections 3.3

and 3.4. Forest development stages are distinguished as in the work of Staines and Welch (1984), namely, establishment-restock stage including trees of age 0 to 8 years, pre-thicket stage with trees of 9 to 14 years old, thicket stage with trees of 15 to 28 years old, pole stage including trees of 29 to 44 years old and finally the mature forest stage with trees of age greater than 44 years old. Relative preferences for different successional stages by red deer have been extracted from the same work. These have resulted from the mean density of pellet groups related to a base of 1 for pole-stage crops.

The yearly cull estimated for the Queen Elizabeth Forest Park has been based on the rapid method recommended by Ratcliffe (1987). He has produced a table (Ratcliffe, 1987, p.23) on which management can be based when sufficient sound data may be lacking. The table contains average figures for red deer populations exhibiting different levels of mortality and fertility at varying densities, which have resulted from experience and previous research. Estimates of the required cull can be made by assessing the proportions of juveniles in the previous cull and reading this off in the table. This also shows the number of males, females and calves to be culled in each square kilometre of forest in order to prevent increase. The cull figure is then calculated by multiplying this number by the area in square kilometres. However, as the same author suggests when sufficient reliable data are available over several years, cohort analysis is a more accurate method to estimate the minimum population size. A cohort includes all animals born in a single year. Cohort analysis involves the recording and accumulation of the number of deer born in a particular year from knowledge of the ages of deer which have been shot. The algorithm is as follows:

STEP 1. Obtain the relative preferences of red deer for habitat types (fully stocked forest, overmature forest and other land) from the work of Staines and Welch,(1984). Calculate the sum and determine the percent frequency of these preferences.

STEP 2. Obtain the relative preferences of red deer for forest development stages from the work of Staines and Welch,(1984). Repeat the same procedure as in STEP 1.

STEP 3. Calculate the total area of each forest habitat type and the area of each forest development stage of fully stocked forest habitat types for different timber management regimes using the subcompartment data base.

STEP 4. Obtain average density of deer per unit area. If this information for a specific forest is lacking, use Cooper and Mutch (1979) and Ratcliffe (1982) studies.

STEP 5. Weight the area occupied by forest habitat types by multiplying area by percent frequency determined in STEP 1.

STEP 6. Calculate the sum of the weighted areas of the habitat types and determine the percent frequency of the weighted areas. Determine the number of deer in each habitat type by multiplying the percent frequency by the average density of deer.

STEP 7. Weight the area occupied by forest development stages by multiplying area by percent frequency determined in STEP 2, for each timber management regime.

STEP 8. Calculate the sum of the weighted areas of the forest development stages and determine the percent frequency of the weighted areas. Determine the number of deer in each forest development stage by multiplying percent frequency of weighted areas by number of deer in each habitat type.

STEP 9. Determine the percent cull using Ratcliffe's rapid method.

STEP 10. Obtain the ratio of permits per shot animal and derive the number of permits per year. Since each Forestry Commission permit is valid for 5 days, calculate the total number of stalking days by multiplying the number of permits by 5. Derive the number of stalking days per unit area by dividing the total number of stalking days by the area of the forest.

The algorithm has been computerized and incorporated in FORM to predict stalking days for different habitat types over time. Results of tentative runs are presented in Chapter 7.

3.6 NATURE CONSERVATION

Nature Conservation relates to low-intensity utilization of natural resources in contrast to broad resource conservation which includes all forms of sustainable management (Peterken, 1985). In practice nature conservation includes: 1) low

-intensity management of ecosystems, so that some natural features would survive in a managed environment. 2) retention of areas in a natural state excluding human impact. Such areas may be sites which are considered representative examples of main types of natural and semi-natural environment, localities of rare plants, breeding sites of rare birds and sites which include important geological features.

In Britain, establishment and management of National Nature Reserves (NRR) and Sites of Special Scientific Interest (SSSI), that is sites of high conservation value are the responsibility of Nature Conservancy Council.

Interaction with forestry interests occurs when land of high conservation value is acquired by the Forestry Commission for afforestation or individuals who own land of this type attempt afforestation motivated by tax-concessions or grant-aids (Nature Conservancy Council, 1986).

There is undoubtely inherent conflict between modern forestry which is based on high-intensity management of forests for increased productivity and nature conservation which, by definition, favours low-intensity management systems. This has created debate between conservation bodies and the Forestry Commission. It is now recognized within the Forestry Commission circles that mistakes have been made regarding afforestation of areas of high conservation value. However, the attitude adopted by the Forestry Commission since mid-seventies (Forestry Commission, 1974) favours management practices which take into account nature conservation. SSSI's and NRR's which fall within Forestry Commission land are at present managed in agreement with the Nature Conservancy Council or in some cases areas are leased to the Council for it to manage (Forestry Commission, 1984a).

In forestry practice, conservation is concentrated around the following three objectives (Forestry Commission, 1986a). First, maintenance of a site, a species or an assemblage of species of national, regional or local conservation value. Second, monitoring of forestry operations, so that damage of sites of conservation value is minimized or avoided. Third, enhancement of wildlife habitats in the woodlands. Achievement of any of these objectives requires identification and mapping of important conservation features, close monitoring of forestry operations by foresters in charge and maintenance of continuity and variety. Continuity is related more to conservation of the existing long-established ancient woodlands, while variety is more important in new plantations where fauna and flora are not established yet.

These management lines are in accord with Peterken's suggestions (1977). He supported the view that management procedures for nature conservation in forests should be based on the concept of Special Scientific Interest, the application of the theory of Island Biogeography to species conservation and the definition and identification of extinction-prone species. He has also distinguished the following types of woodlands which are of Special Scientific Interest for conservation.

1) Relicts of the medieval wood-pasture systems.

2) Ancient high forest woods, that is woodlands originated before 1600, like the native scottish pinewoods and Highland birchwoods.

3) Ancient coppice woodlands which either occupy sites that have been wooded continuously since the Middle Ages or are occupied by trees and shrubs which have not been planted.

4) Ancient woods in inaccessible sites.

5) Woods formed by at least 150 years of natural succession and structural development.

The characteristics of the Island biogeography theory which can be applied to species conservation in the British woodlands can be summarized as follows.

The number of species in a wood at equilibrium is a function of the area and isolation of the wood. This implies that larger woods have more species at equilibrium than smaller woods which tend to have fewer at the same stage. Also isolated woods tend to hold fewer species than those which are closer to other woods.

The woods surviving or created by any change in area or isolation tend towards a new equilibrium. Fragmented forests created by clearance of extensive areas have more species originally than at equilibrium. The rate of loss, however, is faster in small fragments and extinctions exceed immigrations, thus reducing gradually the number of species. In new forests, species come from immigration which is greater than extinction. Equilibrium is reached earlier in smaller woods. The rates of extinction and immigration are equal at equilibrium, although a turnover of species exists.

This theory would apply if all species have an equal probability of survival in woods where they are presently found and an equal probability of colonising woods from which they are presently absent. However, the colonising ability of woodland plants is variable. Species which have a slow colonising ability, relatively small individual populations and are subject to large fluctuations are characterized as extinction-prone. These are numerous, but tend to occur mainly in ancient woodlands. This allows a nature conservation approach to be incorporated in forest management systems by identifying and mapping these sites of high conservation value and differentiating their management from the rest of the forest.

In FORM, nature conservation considerations resulted in the identification of two habitat types, namely, the overmature growth forest stands and the other land habitat type. These two habitat types are included as area constraints in the system. That is, no change or intensive management should take place in the areas occupied by these habitats on a perpetual basis. Another type of nature conservation constraint which is included in FORM relates to the Forestry Commission broadleaved woodlands policy. This policy has been initiated in 1985 (Forestry Commission, 1985) and aims to promote the planting of broadleaved woodlands and encourage the maintenance of broadleaves in the uplands. Conservation interests and limits on operations are detailed in written conservation plans. Such a plan for Aberfoyle Forest District sets a conservation constraint of maintaining at least a minimum of 5% of broadleaves in the forest as a whole in order to promote plant diversity (Forestry Commission, 1986b,1986c). The trade-off results are presented in Chapter 8.

3.7 BUDGETING

The budget method is a well known planning method. It is less technical than the marginal and break-even methods, but it has been proved effective in organization planning.

Basically, the method involves a tabulation of anticipated revenues and costs of each of the alternatives under consideration. It has been incorporated in FORM to produce the budget constraint, since forest managers are usually obliged to follow certain courses of action because of the limited amount of money they command.

The Forestry Commission price-size relationships (Planning and Economic Paper No. 1, 1986) were used to find the money value of the standing timber of conifers. These are relationships which have resulted from statistical analysis of average standing sales prices between 1957 and 1984. Two price-size relationships are available, one for England/Wales and one for Scotland. The relationships for Scotland were selected for the Queen Elizabeth Park.

The critical assumption underlying these relationships is that prices will remain at their average level over the last 30 years, that is price increases were not considered. Also important factors which influence prices like species, quality, terrain, coupe size, distance from major markets and availability of local market demand were not considered. However, their use in the present investigation can be justified, because alternatives are used comparatively. The cost values of all items including in budgeting are average values per treatment type quantity. The cost and revenue values for recreation and deer hunting represent provision and maintenance of appropriate facilities as they are usually incorporated in forest operational budgeting procedures. The costs were derived from various sources, such as, Economic Surveys of Private Forestry (Aberdeen University, 1986,1987), Forestry Commission Headquarters and Aberfoyle Forest District Office. The following forestry operations were included:

FORESTRY COSTINGS

OPERATION	TREATMENT TYPE QUANTITY
1. Ground preparation/ploughing	Ha
2. Planting	Ha
3. Beating up	Ha
4. Weeding	Ha
5. Fertilization	Ha
6. Thinning Conifers	m^3 o.b.
7. Thinning Broadleaves	m^3 o.b.
8. Clearfelling Conifers	m^3 o.b.
9. Clearfelling Broadleaves	m^3 o.b.
10. Recreation	Ha
11. Deer Stalking	

FORESTRY REVENUES

OPERATION	TREATMENT TYPE QUANTITY
1. Standing Sales Conifers	m^3 o.b.
2. Standing Sales Broadleaves	m^3 o.b.
3. Recreation	visitor
3. Deer Stalking	hunter

In the preceding sections of this chapter the response relationships (models) currently incorporated in FORM were described. These are not the only ones encountered in multi-objective forest management. Scenic beauty, water-catchment management and wildlife habitat modelling are some of the other areas which require investigation, so that appropriate relationships will be formulated to be used in multi-objective forest system models. Further research also is required on the models presented in this chapter, since the response relationships are statistical estimates and therefore any predictions based on them will be subject to deviations. The value of these models in their present form lies with: a) the methodology procedures which were used for their derivation; b) the formulation which is suitable for development of multi-objective forest management system models (see chapters 4 and 8); and c) the potential they have to provide a better understanding of forest input-output functions.

CHAPTER FOUR. MULTI-CRITERIA DECISION-MAKING METHODS. AN INTERACTIVE COMBINED APPROACH BASED ON THE MINIMAX CONCEPT

4.1 INTRODUCTION

Multiple criteria decision-making (MCDM) refers to situations where decisions have to be made in the presence of multiple objectives which usually conflict. Several methods mainly originated in the Operations Research field have been developed during the last few decades to deal with problems of this type.

The theme of MCDM approaches is not to determine the 'best decision', but to help decision makers arriving at a decision. This has arisen from the fact that there is no universally acceptable 'best solution' when multiple objectives are considered simultaneously. The point will become more explicit by considering the following problem:

Let X denote a set of possible alternatives with **x** being any member of X. The decision maker wishes to select the best **x** from X considering i number of criteria or objectives, where $i = 1,2,3,...n$ and $f(x) = [f_1(x), f_2(x),....,f_i(x)]$, a vector-valued function that measures the utility of the i^{th} objective.

If $i = 1$, the problem becomes a scalar optimization problem (single objective). Identification of the best solution is an easy task in this case, because any two feasible solutions x^1, x^2 are comparable in terms of the objective function and R^1 is characterized by complete ordering. That is either $f(x^1) > f(x^2)$ or $f(x^1) < f(x^2)$ or $f(x^1) = f(x^2)$. On the interpretation side, in a maximization problem a rational decision maker would select $f(x^1)$ in the first case, $f(x^2)$ in the second one and would be indifferent in the third case as to whether $f(x^1)$ or $f(x^2)$ is the final choice.

If $i > 1$, however, no natural ordering holds. Any two feasible solutions x^1 and x^2 can not be compared any more on the basis of their objective functions, since $f(x^1) = [f_1(x^1),f_2(x^1)]$ and $f(x^2) = [f_1(x^2),f_2(x^2)]$.

Some of the MCDM approaches cope with this lack of natural ordering of R^n by defining a value function $U(f(x))$, such that $U(f(x^1)) > U(f(x^2))$ if and only if $f(x^1)$ is preferred to $f(x^2)$ for any two x^1, x^2 feasible solutions. The majority of MCDM techniques, however, are based on the concept of a nondominated or efficient or Pareto optimal solution. A nondominated (Pareto optimal) solution is defined as a feasible solution if no other feasible solution exists that will yield an improvement in one objective without causing a degradation in at least one other objective.

All MCDM methods, therefore, have to start with some definition of 'best'. This is why most of the research in this field is focused on two issues: First, finding a suitable definition of 'best'. Second, developing a method to determine the best alternative according to the specified definition.

In general, a multi-objective problem in maximization mode can be stated as follows:

$$\text{Max } f(x) = [f_1(x), f_2(x), \ldots, f_k(x)]$$

$$\text{subject to} \quad x \in S,$$

$$\text{where,} \quad S = \{ x \mid g_j(x) \le 0, j = 1,2,\ldots,m; x \in R^n, x \ge 0 \}$$

This format indicates that the decision maker wants to maximize each of these k objective functions simultaneously, subject to m number of constraints on n decision variables, expressed as $x \in S$. The maximization mode does not lead to loss of generality, because it can be converted to minimization mode by multiplying each objective function by -1.

Decision-making when considering multiple criteria is based on interaction between some analyst and the decision maker and explicit or implicit knowledge of preference information.

Although all multi-criteria techniques include a set of criteria of judgement or objectives and a set of decision variables, the preference structure of comparing the alternatives forced many writers to propose different classifications in their attempt to interpret the world of MCDM models. The following sections of this chapter present a discussion of existing classification schemes, a new taxonomic approach more suitable in the context of this investigation and finally the interactive combined method based on the MINMAX concept, which has been incorporated in FORM.

4.2 CLASSIFICATION-DISCUSSION OF MCDM MODELS

Cohon and Marks in 1975 and Cohon later in 1978 distinguished between generating techniques, techniques which are based on the prior articulation of preferences and techniques which require iterative definition of preferences. The first two authors furthermore attempted an evaluation of the multi-objective programming techniques for water planning problems using three criteria, namely, computational efficiency, explicitness of trade-offs among objectives and the amount of information generated for decision-making.

Zionts (1980) used two dimensions for his grouping process: the nature of outcomes, that is stochastic versus deterministic, and the nature of the alternative generating mechanism, that is whether the constraints limiting the alternatives are explicit or implicit.

Ignizio (1982) recognized four groups: methods with geometric measures of goal deviation, efficient sets, interactive methods and combination of approaches. Some different classification was presented by Harrison (1983) on the basis of the value function. For readability he substituted the term value function by utility function and distinguished three broad classes: Techniques which assume no utility function, techniques which require explicit definition of utility function and techniques with implicit utility function.

The credit, however, for the most popular taxonomy goes to Hwang and Masud (1979). They used three dimensions. First, they considered the stage of the solution process at which preference information is needed. This resulted in four groups: no articulation of preference, prior articulation , progressive articulation and posteriori articulation of preference. Their second dimension involved type of information, that is whether the information given by the decision maker is explicit or implicit. Their third dimension included major classes of methods. Evans in 1984 used the same taxonomic structure as Hwang and Masud, but included two more criteria, continuity and linearity.

Finally, Romero and Rehman (1984,1985) distinguished two broad categories for potential applications of multi-criteria approaches in farm planning on the basis of their mathematical structure: goal programming (GP) and multi-objective programming (MOP).

Figure 2 shows a more comprehensive classification scheme resulting from the synthesis of most of the works reported in the previous paragraphs. I believe that this scheme is more suitable for the interpretation of the MOP forestry application under investigation.

The first distinction is made on the basis of the nature of the problem. Two types are usually met in most multi-criteria problems: discrete and continuous.

Discrete problems are those which are characterized by a set of predefined alternatives available before the multi-objective part of the analysis begins. Transportation plans fall in this category.

For continuous problems on the other hand, a mathematical model including decision variables, constraints and multi-objective functions has to be formulated in order to generate the alternatives. Continuity implies that the decision variables, which are representatives of the alternatives can take on any values that still meet the constraints of the system.

The methods developed for discrete problems are known in the MCDM literature as multi-attribute decision-making (MADM) methods. These require information about the decision maker's preference among values of a given attribute and across attributes. Their structure involves four elements: First, a set of predefined alternatives

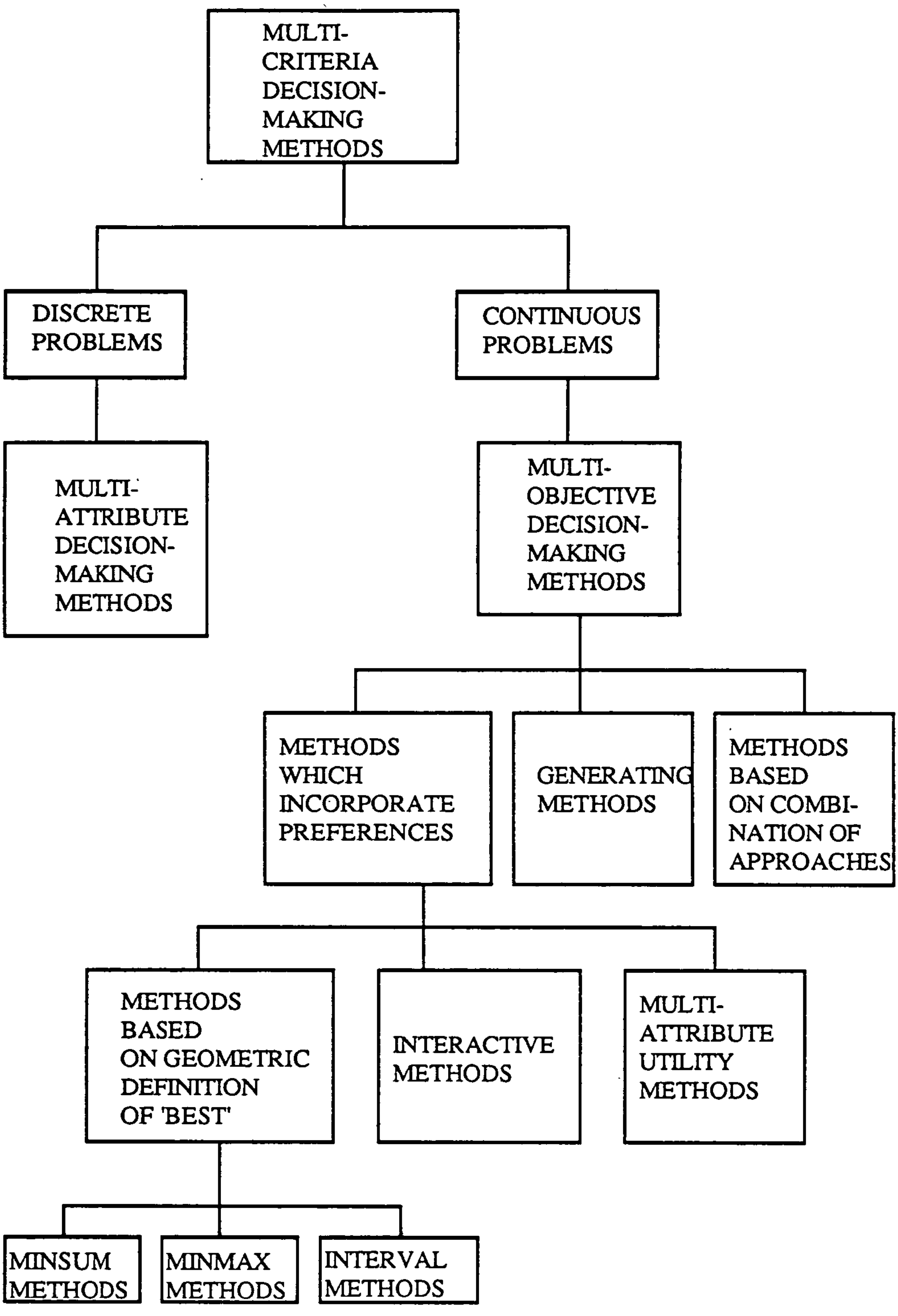


Figure 2. Classification of multi-criteria decision-making methods

with attribute values attached to them. Second, scalings of attribute values or an ordering across attributes. Third, a set of constraints across attributes. Fourth, a process mechanism to compare the attribute values of the alternatives, so that alternatives can be sequentially either eliminated or retained. Roy (1971,1973) introduced the concept of outranking relations in the multiple criteria decision-making field, which has been the basis of the most well known technique in terms of applications. Other work with MADM techniques has been carried out by Green (1973), who used multi-dimensional scaling and conjoint measurement in relation to the scaling aspects of multi-attribute choice models. McCrimmon (1973) and Zionts (1980) presented a good review and discussion of MADM methods. No further analysis of these, however, is attempted here, since the problem considered in FORM is a continuous one and therefore the multi-objective decision-making (MODM) methods are of more interest in this research work.

MODM techniques are distinguished in Figure 2 in three broad classes on the basis of the decision maker's preference requirements:

4.2.1 METHODS WHICH INCORPORATE PREFERENCES

The solution process of all these methods depends heavily on preference information elicited from the decision maker at some stage. The 'best', however, is defined differently in the various approaches which fall in this category and this has formed the criterion for a further distinction of these methods in three subclasses.

4.2.1.1. METHODS BASED ON GEOMETRIC DEFINITION OF BEST

These techniques rely on the statement of preferences prior to the solution process of the multi-criteria problem. The preference statement is taken as the basis for complete ordering of the objectives, so that a number of feasible solutions can be eliminated by any new ordering. From the mathematical point of view another step can be added in this taxonomic ladder. This results in three subgroups:

A. MINISUM techniques: They attempt to minimize the sum of undesirable deviations from the goal set.

B. MINIMAX techniques: They minimize the maximum deviation from any goal within the total set of goals.

C. INTERVAL techniques: Instead of minimizing some geometric measure of deviation from a single value they consider an interval of acceptable values.

The most popular method from the MINISUM group is goal programming. The structure of a multi-criteria problem in goal programming mode must have three basic elements. A set of objective functions expressed as mathematical functions of a number of decision variables, which act as representatives of the alternative courses of action of the problem, a set of resource constraints expressed also as mathematical functions of a number of decision variables and a set of right hand side values. These values when attached to the objective functions are called targets and constitute the goals which the decision maker wishes to attain. This means that these values may not be achieved. The right hand side values of the constraints, however, represent resource limitations and they usually have to be satisfied, although in the goal programming framework they can be violated by amounts measured by deviational variables (Romero and Rehman, 1985). The mathematical formulation in vector maximum model is as follows:

$$\text{Min} \quad [\sum_{j=1}^{k} (d_j^- , d_j^+)^p]^{1/p} , \; p \geq 1$$

subject to

$$g_i(x) \leq 0, \quad i = 1,2,3,....,m$$

$$f_j(x) + d_j^- - d_j^+ = b_j, \; j = 1,2,,3,....,k$$

$$d_j^-, d_j^+ \geq 0 \quad \forall j$$

$$d_j^- . d_j^+ = 0 \quad \forall j$$

where, b_j represent the target values specified by the decision maker for the objectives, d_j^-, d_j^+ are the deviational variables for underachievement and overachievement respectively of the j^{th} goal, added to the goal inequalities, which are thus converted to equalities. The final equation of the constraint set implies that for each of the j goals one of the deviational variables must be zero, that is a goal can not be both under- and over-achieved. p depends on the utility function of the decision maker.

The most popular variants of goal programming are the lexicographic (LGP) and weighting (WGP) forms. In the first, pre-emptive weights are used to accomplish the minimization process. A sequence of minimization problems is solved with the higher ranked goals satisfied first. The achievement function in this case becomes:

$$\text{Min} \; [\; h_1(d_j^-,d_j^+), \; h_2(d_j^-,d_j^+),......, h_l(d_j^-,d_j^+)],$$

where, $h_i(d_j^-,d_j^+)$, $j = 1,2,3,....,l$ are functions of the deviational variables.

The algorithm stops when any of the problems solved in the ranked sequence has no optimal alternative solutions (dual degeneracy). The lower priority goals thus are considered as redundant.

In weighted goal programming a function which consists of the sum of all weighted deviational variables is minimized. The weighting of the deviational variables is done relatively to the importance each goal has for the decision maker.

Goal programming has been the most widely used of all multi-criteria approaches for various types of problems (Cohon, 1978; Charnes, Cooper, Lewis and Niehaus, 1976; Karwan and Wallace, 1980; Ignizio, 1982; Field, 1973; Schuler and Meadows, 1975). What is considered as the main advantage of goal programming is that it only requires ordinal ranking of the objectives, that is, weights need not be specified numerically. Also in computation the Simplex Algorithm, with which many managers are well acquainted can be used.

Criticisms have arisen, however, on the following points for LGP:

1) Trade-offs can only be made between goals of the same priority, while the value preference across goals is infinity (∞). 2) Goals within the same priority must be commensurable or become commensurable by means of weights. 3) The goal priorities must be pre-empted, although Ignizio (1982) supported that an orthodox linear programming problem is a special case of LGP and pre-emption of goal priorities is well documented in the real world decision-making. 4) From the theoretical view point there is obscurity as to what exactly is optimized and this extends to all goal programming variants, because it stems from its basic structure. It is, nevertheless, this point that makes goal programming superior to conventional linear programming in practice, since its structure is far more representative of the real world (Ignizio, 1982; Romero and Rehman, 1984).

Criticism has also been addressed to the WGP. It refers to the fact that the instantaneous trade-off rate between any two objectives or, in economic terms, the marginal rate of substitution, can take on only four values. This does not comply with the economic theory, which supports that these rates would change as the level of benefits of the objectives change.

The MINIMAX concept, that is the minimization of the maximum deviation of any goal from a fixed point, underlies the fuzzy programming approach (Zimmerman, 1978; Ignizio, 1982). In fuzzy programming two values, for example U_k and L_k, are attached to each objective. U_k should represent the desired level of achievement for objective k, while L_k the lowest acceptable level of achievement for objective k.

Let, $d_k = U_k - L_k$ denote the leeway for objective k. A membership function then μ_k (x) should be attached to each goal so that

$$\mu_k(x) = \begin{cases} 1 & \text{if } Z_k \geq U_k \\ 0 < \mu_k(x) < 1 & \text{if } L_k < Z_k < U_k \\ 0 & \text{if } Z_k \leq L_k \end{cases}$$

where, Z_k are the achieved values of the objectives. This relationship implies perfect achievement for values of 1, strong non-achievement for values of 0 and non-achievement for intermediate values, that is values between 0 and 1. The solution to the model then is found by maximizing the minimum value of $\mu_k(x)$, or in other words minimizing the worst under-achievement of any goal. The problem to be solved is as follows if the membership function is linear:

$$\text{Min } \lambda$$

$$\text{subject to} \qquad \lambda \geq (U_k - Z_k / d_k) \quad \text{for all } k$$

$$x \in S$$

where, λ is some dummy variable and S the set of the constraints.

The main advantages of this method is that it transforms the multi-criteria problem to an orthodox single objective problem, while constraints and objectives (in the form of goals) are treated symmetricaly. This is considered more consistent with real world decision-making. However, some drawbacks are also associated with this approach. The under-achievement of just one goal can have a major impact on the solution, since the problem that is solved is minimization of the maximum under-achievement. The form of the membership function is also difficult to define with accuracy.

The INTERVAL methods may use either the MINISUM concept or the MINIMAX one.

Other variants of goal programming have also been investigated to more realistically represent various types of problems. These include fractional goal programming (Kornbluth and Steuer, 1981), whereby objective functions are expressed as fractionals of the form $c_i x + a_i / d_i x + b_i$ and penalty functions within goal programming structure. Fractional goal programming, for example, is considered more appropriate in financial and corporate planning problems, where profit is usually expressed as the ratio of debt/equity or production planning, where costs are better represented as a ratio of inventory/sales. These approaches were not considered appropriate in the multi-criteria framework of the forestry application. Ignizio (1983) introduced the term 'generalized goal programming' to classify all these extensions of goal programming. He included in this class the MINISUM and MINIMAX methods, which in Figure 2 are treated separately.

4.2.1.2 INTERACTIVE METHODS

These techniques utilize the concept of compromise solution for the definition of 'best'. Their solution process depends highly on input information from the decision maker, which is derived in a progressive way. The general approach consists of three steps: a) Find a nondominated solution b) Interact with the decision maker and modify the problem accordingly and c) Repeat the previous two steps until the decision maker is satisfied or some termination rule is applied. The interaction between the analyst and the decision maker may be explicit or implicit.

Geoffrion (1967) presented a method which requires specification of a utility function to identify the best-compromise solution, instead of generating the entire set of nondominated solutions. The method assumes, however, that the utility function U is a monotonically nondecreasing ordinal function in each objective, that is $\partial U/\partial f_i>0$, or in other words the marginal utility is positive in the neighbourhood of any feasible point $\mathbf{x}^i$, and also U should be quasi-concave.

Geoffrion, Dyer and Feinberg (1972) developed further a large-step gradient algorithm in the context of the Frank-Wolfe algorithm, which is a non-linear programming method (Dyer, 1974). The decision maker has to specify an overall utility function based on the values of the objectives. This process need not be explicit as local information is only required to perform the computations. The algorithm starts from an initial feasible point and continues eliciting information interactively from the decision maker about the direction of improvement and the step size on this direction. A sequence of improved feasible solutions is obtained, which finally converges to an optimal solution.

The drawback of this technique is the difficulty the decision maker experiences in providing information. Dyer (1973) proposed a trade-off estimation procedure, which through dialogue between man and machine helps estimating the step size, but still the algorithm lacks systematic assessment for trade-offs and the decision maker's desires are not actively expressed in the final solution. Harrison (1983) attempted to elaborate the method furthermore and produced a very interesting variant which combines an implicit estimation procedure for the marginal rate of substitution.

Haimes and Hall (1974) developed the Surrogate Worth Trade-off Method, motivated by the fact that the trade-off can be found from the values of the dual variables associated with the constraints. Therefore, optimal weights should be relative to the levels of the objective functions. The algorithm starts by computing the ideal solution for each objective and selecting a reference objective (f_l), arbitrarily. A set of trade-off functions is constructed by solving the following problem:

$$\text{Max } f_1(\mathbf{x})$$

$$\text{subject to} \quad f_j(\mathbf{x}) \geq \varepsilon_j, \quad j = 1,2,3,....,k$$

$$g_i(\mathbf{x}) \leq 0, \quad i = 1,2,3,....,m$$

where ε_j are the deviations from the ideal values, which are varied parametrically to generate the set of nondominated solutions, that is the ones which have non-zero values for the trade-off functions, $\lambda\varepsilon_j = -\partial F_e / \partial F_j$.

The values of F_j and $\lambda\varepsilon_j$ are presented to the decision maker in order to assess the surrogate worth function w_{ej}. The solutions which have $w_{ej} = 0$ for all j are termed indifference solutions and any of these is a preferred solution. If no indifference solutions exist, approximate relations of all worth functions are developed to find the optimal one.

There are two main advantages of the method. First, the decision maker has only to consider two objectives at a time when assessing the worth function. Second, the method can deal with a variety of problems, linear and non-linear, static and dynamic and can also be extended to problems with multiple decision makers (Hall and Haimes, 1976). However, some preferred solutions may be left out because of arbitrary change of epsilon values, while the decision maker may be misled, because the marginal trade-off values ($\lambda\varepsilon_j$) are indicated only in a very small area around the current solution. Also the computational burden is increased with the number of objectives.

Another representative interactive method with explicit trade-offs is the method of Zionts and Wallenius presented first in 1976 and extended in 1983. The method starts by initializing arbitrarily a set of positive weights $\boldsymbol{\lambda}$ and optimizing a composite function with these weights to produce a nondominated solution. From the set of non-basic variables a subset of efficient solutions is selected and trade-offs for each solution are defined. A number of these trade-offs is presented to the decision maker, who is asked to reply 'yes', 'no' or 'do not know' regarding preference of the trade-offs. From the decision maker's replies a new set of weights is generated and a new nondominated solution is found. The process iterates until the decision maker is satisfied with a set of trade-offs. The utility function assumed is implicit and the method guarantees convergence in a finite number of iterations. However, it is difficult to require the decision maker to have a reasonable implicit utility function.

The most 'classic' interactive methods with implicit trade-offs are the STEM method, the Compromise programming and the Interactive MOLP method.

Benayoun, DeMontgolfier, Tergny and Larichev (1971) are credited with the development of STEP-method (STEM). STEM operates in three steps: 1) Construction of a 'payoff table' by establishing an ideal point, after solving for each objective function, subject to the set of constraints. 2) The nearest nondominated solution in the MINIMAX sense is sought by solving:

$$\text{Min } \lambda$$

$$\text{subject to} \quad \lambda \geq (f_j^* - f_j(x)) * \pi_j, \; j = 1,2,3,....,k$$

$$x \in S$$

$$\lambda \geq 0$$

where, S is the constraint set, f_j^* is the ideal solution and

$$\pi_j = \frac{a_j}{\sum_{j=1}^{k} a_j}, \qquad a_j = \frac{f_j^* - f_j^{min}}{f_j^*} \left[\frac{1}{\sqrt{\sum_{i=1}^{n} (c_{ji})^2}} \right], \qquad \text{if } f_j^* > 0$$

$$a_j = \frac{f_j^{min} - f_j^*}{f_j^{min}} \left[\frac{1}{\sqrt{\sum_{i=1}^{n} (c_{ji})^2}} \right], \qquad \text{if } f_j^* \leq 0$$

c_{ji} are the coefficients of the j^{th} objective. The term in brackets is a normalization factor for the objective functions. 3) The compromise solution is presented to the decision maker, who has to compare its value function with the ideal one. If some objective values are not satisfactory, the decision maker may relax a satisfactory objective to improve a non-satisfactory in the next iteration. The algorithm stops in a finite number of iterations, usually equal to the number of objectives, but it assumes no compromise solution if the decision maker is not satisfied within the iterative cycle. This does not always comply with real situations, where some compromise decisions must be made.

Compromise programming is based on the concept of the compromise set and was developed by Zeleny (1973,1974,1976a). The method starts by generating N, the set of nondominated solutions using some multi-objective linear programming algorithm. It then establishes the ideal alternative as follows:

Let X be the set of initial feasible alternatives. X generates a vector

$$f_i = [\, f_i(x_1), f_i(x_2), \ldots\ldots, f_i(x_k)]$$

where k is the dimensionality index, representing the achievable levels of the i^{th} attribute. Among all these levels there is at least one extreme or ideal value, which is preferred to all others. This is termed anchor value and it is written as:

$$f_i^* = \max_{j \in k} f_i(x_j), \quad i \in R$$

Both maximum and ideal values are included in the concept of the anchor value for simplification. The set of all such anchor values constitutes the ideal alternative, denoted as:

$$f^*(x) = [\, f^*(x_1), f^*(x_2), \ldots\ldots, f^*(x_k)]$$

The ideal alternative is generally infeasible, otherwise no conflict is present and therefore no decision-making involved. It is postulated that the infeasibility of the ideal is the source of pre-decision conflict. The method proceeds by finding a subset of N, termed compromise set C^{i}. The compromise set is defined as the set of all solutions which are 'as close as possible' to the ideal solution, with respect to one or more distance measures (L_p-metrics).

If the compromise set C^i is small enough, so that the decision maker can choose a satisfactory solution, the algorithm stops. Otherwise, some compromise solutions are discarded, a new ideal is computed, because the old one is displaced closer to the feasible set and a new iteration begins.

The term 'as close as possible' is a fuzzy term, which relates to the theory of fuzzy sets and deserves some further explanation.

According to the axiom of choice (Zeleny, 1976a) the alternatives that are closer to the ideal are preferred to those that are further away. To be as close as possible to the ideal is the rationale of human choice. Intensity of preferences are assigned linguistic rather than numerical values (Zadeh, 1973). Although linguistic terms lack precision and mathematical formalism, they are more representative of the fuzziness of human thoughts and preferences.

A fuzzy subset A of a universe of discourse U is characterized by a membership function μ_A, which associates with each element y of U a number $\mu_A(y)$ in the interval [0,1], which represents the grades of membership of y in A. The levels of the ith attribute can be viewed, therefore, as a fuzzy set defined as the set of pairs $\{ f_i(x_j), d_i(x_j)\}$, $i \in R$, $j \in k$, where, $d_i(x_j)$ is a membership function mapping the levels of the i^{th} attribute into the interval [0,1].

The degree of closeness of any alternative $f_i(x_j)$ from the ideal $f^*(x_i)$ is defined as

$d_i(x_j) = 1,$ if $f_i(x_j) = f^*(x_i)$ and

$0 \leq d_i(x_j) \leq 1$ for $i \in R$, $j \in k$

The functions yielding the degree of closeness to $f^*(x_i)$ for any alternative are:

1. $d_i(x_j) = f_i(x_j) / f^*(x_i)$ if $f^*(x_i)$ is a minimum
2. $d_i(x_j) = f^*(x_i) / f_i(x_j)$ if $f^*(x_i)$ is a maximum
3. $d_i(x_j) = 1/2 \, [f_i(x_j)/f^*(x_i) + f^*(x_i)/f_i(x_j)]$ if $f^*(x_i)$ is a feasible goal value or the ideal

Thus, the degree of closeness of any alternative $f_i(x_j)$ from the ideal $f^*(x_i)$ is reflected in terms of $d_i(x_j)$ and $d^*(x_i)$. In other words, the set of feasible alternatives X is mapped first through $f_i(x_j)$'s into a 'criterion' space and then through $d_i(x_j)$'s into a 'distance' space. To evaluate the distance between each alternative and the ideal the following family of distance membership functions is used:

$$L_p(\boldsymbol{\lambda}, j) = \left[\sum_{i=1}^{r} \lambda_i^p (1 - d_i(x_j))^p \right]^{1/p}$$

where, $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \ldots, \lambda_r)$ is a vector of attribute attained levels $\boldsymbol{\lambda}_i$ and p is the distance parameters with values $1 \leq p \leq \infty$. So the closest alternatives to the ideal are these minimizing $L_p(\lambda,j)$ for some value of p.

Since $L_p(\lambda,j)$ is a strictly increasing function of

$$Lp'(\lambda,j) = \sum_{i=1}^{r} \lambda_i^p (1 - d_i(x_j))^p,$$

the exponent 1/p can be omitted with no effect on the compromise solution, that is the minimum value of $Lp(\lambda,j)$ is identical to that of $Lp'(\lambda,j)$.

λ_i weights distances according to the attributes, irrespective of their magnitude. p weights distances according to their magnitudes and across the attributes. For p=1 and p=2 the longest and the shortest distance respectively in two dimensional Euclidean space is considered. As p increases more weight is being given to the largest distance $(1- d_i(x_j))$. For $p=\infty$ (the Tchebychev distance) the largest distance completely dominates and

$$L_\infty(\lambda,j) = \max_i \{ \lambda_i (1 - d_i(x_j)) \},$$

that is the maximum of the individual distances is minimized. Distance functions for p>2 are not used in the two dimensional Euclidean sense. They simply indicate preferences by giving a measure of proximity between each alternative and the ideal solution. For different values of p and λ different compromise solutions are generated. Compromise solutions (x_{jp} and $y_{jp} = y(x_{jp})$) enjoy a number of very useful properties defined by Yu (1973) and Yu and Leitmann(1976): 1) Feasibility 2) Individual rationality 3) Least group regret. A regret function is defined as:

$$R_p(y) = \|y^* - y\|_\gamma = [\sum_j (y_j^* - y_j)^p]^{1/p}, \ p > 1$$

4) No dictatorship 5) Pareto optimality 6) Uniqueness 7) Symmetry 8) Independence of irrelevant alternatives 9) Continuity 10) Monotonicity and bounds and 12) Monotonicity of the group utilities and the individual regrets.

Also work with compromise solutions has been conducted by Gearhart (1979), Dinkelbach and Iserman (1973), Ecker and Shoemaker (1980) and Steuer and Choo (1983). Compromise programming does not require much information from the decision maker during the interactive procedure, while allows incorporation of non-commensurable conflicting or fuzzy objectives. It does, however, use the multi-criteria Simplex method to generate the set of all nondominated solutions, which must still undergo refinement and it can not deal with large problems.

The Interactive MOLP method has been developed by Steuer (1975a,1976,1977). The purpose of the method is to identify the best solution from reduced subsets of the very large nondominated solution set which is usually generated by solving the multi-objective vector maximum problem. This is attempted using the concept of the gradient cone interactively. A gradient cone is defined to be the convex cone generated by the gradients of the different objectives. (Note that a gradient of a function, denoted as ∇ f or grad f, is the vector whose elements are formed by the partial derivatives of the function). The larger the gradient cone, the larger the number of efficient extreme points. 2k+1 convex combination trial gradients (nondominated extreme points) are employed in each iteration, where k is the number of objective functions.

Each of these leads to a single objective linear programming problem:

$$\max \ \lambda^{jT} Cx$$

$$\text{subject to } \ x \in S$$

whose optimal solution is a nondominated extreme point of the original vector maximum problem. The decision maker has to select one and a new contracted gradient cone of the same geometric proportions and orientation as the previous one, but of $1/k^{th}$ cross-sectional volume is generated. The new cone is computed from the current one using interval criterion weights. No mathematical expertise is required on behalf of the decision maker and the method converges in a finite number of iterations. However, it assumes a monotone or quasi-concave utility function, making it suitable only for linear problems.

4.2.1.3 MULTI-ATTRIBUTE UTILITY METHODS

These methods require specification of a utility function from the decision maker. The structure of a typical multi-attribute utility problem is as follows:

$$\text{Max } U[F(x)] = U[f_1(x), f_2(x), \ldots, f_k(x)]$$

$$\text{subject to } g_j(x) \leq 0, \; j = 1,2,3,\ldots,m$$

where, U[f(x)] the utility function of the multiple objectives.

The utility function should be a measure of the decision maker's preferences and must be constructed prior to the solution process. The rationale for using a utility function is that all real decision makers usually have a utility associated with the objectives. The concept is similar to that used in consumer theory in economics. To specify a utility function, however, is very difficult even for small problems. Two basic forms are assumed in the literature (Keeney, 1972; Fishburn, 1974; Bell, Keeney and Raiffa, 1977):

1) the additive form, whereby the problem becomes:

$$\text{Max } U[F(x)] = \sum_{i=1}^{k} U_i f_i(x) \qquad \text{and}$$

2) the multiplicative form, whereby the problem to solve is:

$$\text{Max } U[F(x)] = \prod_{i=1}^{k} U_i f_i(x)$$

These are very simplified forms, which have been established in the literature because it is much easier to compute k unidimensional utility functions than a composite utility function directly.

Variants of the basic multi-attribute utility method use weights to indicate the importance of the objectives. This is because the slope of the tangent of the indifference curve and the nondominated solution set is proportional to the ratio of the optimal values of the weights. It also means that if the optimal weights can be determined, the most satisfactory solution is guaranteed. This is the main advantage of the utility methods. However, the weights are usually subjective estimates of the decision maker and do not represent optimal values.

4.2.2 GENERATING METHODS

This group of methods solve multi-objective problems by generating the set of all nondominated solutions and the set of all nondominated function values. Interaction with the decision maker occurs at a posteriori level, that is after the solution process has been established. They impose high computational burdens because of the large number of nondominated solutions associated with multi-objective programming. Various methods have been suggested to generate the set of nondominated solutions. The best known are discussed in the following paragraphs.

The weighting or parametric method (Zadeh, 1963; Gal and Nedoma, 1972) solves a single objective problem by forming a composite function from the sum of all objectives after a weight is assigned to each objective. It assumes that the relative importance of the weights is known and constant. The weights are parameters, which are normalized ($\Sigma w_i=1$, $i=1,2,...,k$), and varied so as to locate the nondominated points. If the problem is linear, the whole set of nondominated solutions is generated. Work based on the weighting method was published by Zeleny in 1974. He suggested decomposition of the parametric space of weights to generate the efficient set. This approach refers also to linear problems.

The constraint method (Marglin, 1967; Cohon and Marks, 1973) locates the preferred solution by optimizing one objective function, treating the rest as constraints. The right hand side values of these objectives-constraints are minimum allowable levels, which are varied systematically to yield the nondominated set. Determination of these minimum levels, however, is subject to questions when solving real problems.

The noninferior set estimation (NISE) method developed by Cohon (1978) is a different approach from the weighting and constraint methods in that it attempts to approximate the noninferior set rather than generating all noninferior points. The accuracy of the approximation is controlled through a predetermined error criterion compared to the maximum possible error at each iteration. The method works for linear problems with less than three objectives.

Multi-objective linear programming(MOLP) methods (Yu, 1974; Yu and Leitmann, 1974; Aubin, 1973; Ecker and Kouada, 1975; Ecker and Kouada, 1978; Philip, 1972; Steuer, 1975b; Steuer, 1976; Zeleny, 1974; Zeleny, 1976b; Evans and Steuer, 1973; Sengupta,Podrebarac and Fernando, 1973; Kornbluth and Steuer, 1980) are also generating techniques. A typical MOLP problem in vector maximum mode is structured as follows:

$$\begin{aligned} &\text{Max } Cx \\ &\text{subject to } Ax = b \\ &x \geq 0 \end{aligned}$$

where, C is a k X n objective function coefficient matrix, A is an m X n constraint function coefficient matrix, **x** is an n X 1 decision variable vector, **b** is an m X 1 constant vector and **0** an n X 1 null vector. The basic assumptions of the MOLP methods are the linearity of functions and the convexity of the nondominated set. Any nondominated point, therefore, can be expressed as a convex combination of the set of nondominated extreme points. Most of these methods involve three distinct phases in their solution process: a) Finding an initial feasible extreme point b) Finding an initial efficient extreme point and c) Finding all efficient extreme points. Phase c can be accomplished using any of the following three approaches:

1. Parametric variation, which has been discussed in weighting and constraint methods.
2. Adjacent nondominated basis approach, which involves pivoting and testing for nondominance among all bases.
3. Adjacent extreme point approach, which generates the efficient set by moving from the one extreme (nondominated) point to adjacent extreme points.

4.2.3 COMBINATION OF APPROACHES

Any of the individual methods in the previous groups can be combined to form a new method better fitted for the actual problem at hand. A combined approach of the MINIMAX concept and the generating approach, which has been incorporated in FORM is presented in the next section.

Evaluation of any multi-criteria decision-making method for real world applications should be made with regard to the specific decision structure and environment. All methods have advantages as well as weaknesses, as it has been discussed in the preceding paragraphs.

Generating techniques overcome the problem of weighting objectives, but impose a great computational burden ,although some remedies have been suggested in the literature. Preference methods on the other hand rely on weights or ranking for their solution. Interactive methods, it is claimed, make the decision maker part of the solution process, but in most cases require much information. In my opinion a combination of approaches should be attempted for real world problems, so that special features of decision problems can be favourably exploited and drawbacks of existing methods may be diminished or eliminated.

Unfortunately applications to real world problems are still rare and therefore, the question of evaluation of multi-criteria decision-making approaches is important. However, experience with multi-objective analysis has shown that two criteria are quite vital for any rational choice:

- Type and size of the problem
- Characteristics of the decision maker.

The first criterion is related to the nature of the problem (linearity/non-linearity, dimensionality) and its decision structure. It is also connected to computer resources, that is cost and time in the form of availability of codes and computational experience.

The second criterion is associated with the decision maker's information burden to the solution process, ability to understand the method, and, confidence in the final solution provided by the method.

4.3 A COMBINED APPROACH BASED ON THE MINIMAX CONCEPT

This method combines various concepts of compromise programming regarding L_∞-norm (Yu, 1973; Zeleny, 1973; Zeleny, 1982; Ecker and Shoemaker, 1980; Gearhart, 1979), the filtering method of Steuer and Harris (1980) and the reference objectives ideas of Wierzbicki (1980). The approach as it has been incorporated in FORM forms part of a more generalized method published by Steuer and Choo (1983), that is FORM considers only linear functions and convex sets. The method is in the following paragraphs.

The ideal criterion vector is established first. Its co-ordinates are formed from the maximum value each objective function attains, when optimized alone and subject to the set of constraints. Mathematically, this can be written out as following:

Let $z^* \in R^k$, then $z_i^* = \max\,[f_i(x)] + \varepsilon_i$

subject to $x \in S$

where, S is the constraint set

$i = 1,2,3,\ldots\ldots,k$ with k the number of objective functions

$\varepsilon_i \geq 0$

ε_i in computational practice is set equal to a very small positive scalar.

The nondominated vectors which are closer to the ideal vector are computed then in the MINIMAX sense. That is, the distance between any criterion vector $z \in F$ and the ideal criterion vector z* is:

$$\|z^* - z\|_\infty^\lambda = \max\,[\lambda_i |z_i^* - z_i|],$$

where, $i = 1,2,3,....,k,$

$$\boldsymbol{\lambda} \in R^k, \quad \lambda_i \geq 0,$$

$$\sum_{i=1}^{k} \boldsymbol{\lambda}_i = 1$$

This relationship is also called Tchebychev norm. $F \in R^k$ is the set of all feasible criterion vectors, that is the set of images of all $\mathbf{x} \in S$ under the f_i.

$\boldsymbol{\lambda}$'s are weighting vectors generated internally by the algorithm. A random number generator is employed in FORM to draw them and convex combinations then are formed.

Steuer and Harris (1980) have discussed pitfalls when forming convex combinations of efficient extreme points. It is risky and unsatisfactory to finitely represent the solution set with the efficient extreme point criterion vectors, because when generating the whole efficient set of an MOLP problem, the solution set is typically a nonconvex set of the surface of the feasible region. Therefore, some areas of the efficient set are under-represented and some others over-represented. To obtain evenly dispersed representatives, convex combinations of the efficient extreme point criterion vectors have to be generated to fill in the under-represented areas, while the surplus has to be discarded in the over-represented areas.

These authors compared convex combinations a) drawn in a pre-specified way b) drawn from the uniform distribution 0-1 c) drawn from the Weibull distribution. In the first case, they found that although the weighting vectors were constructed so as to be as different as possible from one another, the convex combinations generated were not well distributed. In the second case, they drew a large number of weighting vectors from the uniform 0-1 distribution and formed the set of convex combinations as:

$$\sum_{i=1}^{k} \boldsymbol{\lambda}_i x^i \quad \text{and} \quad \boldsymbol{\lambda}_i = \frac{\upsilon_i}{\sum_{i=1}^{k} \upsilon_i},$$ υ_i is the draw from the uniform 0-1 distribution.

The most redundant weighting vectors from the set of convex combinations were dropped, but the facet defined by the various $\mathbf{x}^i$ points revealed a multi-normal type of build up around its central area. The third case was their attempt to overcome this problem drawing υ_i from the Weibull distribution. Random numbers of the Weibull variate W:b,c were computed from the relationship: W:b,c ~ $b(-\log R)^{1/c}$, where R is a unit rectangular variate (Hastings and Peacock,1974). For low values of b and c parameters the facet obtained from the various $\mathbf{x}^i$ points showed a concentration of points at its corner.

In FORM, 50% of υ_i are drawn from the uniform 0-1 distribution and 50% from the Weibull distribution. This was decided to achieve a better balance of the convex combinations of the weighting vectors.

The next step of the method is to generate the entire set of nondominated criterion vectors for the different $\boldsymbol{\lambda}$'s. However, it would be of little help to forest managers to be presented with a very large number of alternative solutions (300 or 400, for example) to choose from. To overcome the problem the 'filter' method of Steuer and Harris (1980) was employed. The set of nondominated solutions ($N \subset F$) closest to the ideal vector ($\mathbf{z}^*$) for each of the weighting vectors ($\boldsymbol{\lambda}_i$'s) according to the Tchebychev norm ($p = \infty$) is generated only.

Other efforts in the literature to reduce the set of nondominated solutions are these of Morse (1980) and Törn (1980). Morse used cluster analysis considering as general evaluative criterion some minimum redundancy. He recommended hierarchical methods to minimize redundancy. Törn's work was rather similar to Morse's, although it was carried out separately about the same time.

The 'filter' method is based on the following relationship used to determine dissimilarity between the vectors submitted to the test:

$$\left[\sum_{i=1}^{k} (\pi_i |z_i^t - z_i^h|)^p\right]^{1/p} < d$$

where, k is the number of objective functions

z_i is the i^{th} criterion vector element

t is the identification superscript of the vector undergoing the test

h is the identification superscript of the vector currently retained by the filter

p is a parameter which identifies the family of L_p-metrics to be used

$p = 1,2,\ldots,\infty$

d is the test-distance parameter

π_i is the gradation weight

π_i's are scaling factors which are used to balance the difference value ranges of the vectors input to the filter. They are estimated as follows:

$$\pi_i = [\, R_i \sum_{j=1}^{k} \frac{1}{R_j} \,]^{-1},$$

and, R_i denotes the range of criterion values of the ith objective defined as,

$R_i = \max(z_i^t) - \min(z_i^t)$, $t \in T$, where T is the set of the identification superscripts of the vectors which have to undergo the test.

The filtering process begins by selecting a first value for the test-distance parameter d. Conventionally the first vector read in the test is called forward seed point and is always retained. The second vector is retained with the following procedure: All the remaining vectors are processed through the filtering relationship and their gradation weighted distances away from the forward seed point are calculated according to an L_p-metric. In FORM the L_∞-norm is used. Vectors with distances less than d are discarded, because they are considered similar. From the remaining ones, the vector with the smallest distance away from the seed point is retained as the second vector. To identify the third vector to be retained, each of the remaining ones is processed again through the filtering relationship and their gradation distances away from the seed point and away from the second vector retained are calculated. The ones with distances less than d are again discarded, while from the remaining vectors , the one with the lowest sum of the two distances is retained as the third point.

The procedure continues in the same fashion until the desired size of the filtered set is achieved. This depends on the value of the test-distance parameter d. d has to be found by experimentation. If a larger filtered group is aimed, then a smaller value of d must be used and vice versa. Steuer and Harris (1980) suggested that 'the halving and doubling' technique of Luenberger (1973) can be used to more systematically experiment with d values.

At the present development stage of FORM no such facility is included. A first tentative value is recommended by averaging the data points submitted to the test. No difficulty has been experienced when implemented FORM to the Queen Elizabeth Forest Park scenario by the trial efforts to obtain the right value of d with regard to the desired size of the filtered group (see also chapter 8).

The same filtering relationship has been used to construct another test which has exactly the opposite function. That is, to help the forest manager refine his final choice another group of vectors can be generated in the neighbourhood of the one just selected. The one selected is called reverse seed point. A ranking routine has been incorporated in FORM to order the most similar vectors to the reverse seed point from closest to the furthest according to their gradation distances away from the seed. During this phase, therefore the vectors with gradation distances less than d are retained.

By applying the filtering routine sequentially, smaller subsets of the set of nondominated solutions are presented to the manager at each iteration.

The following lexicographic MINIMAX optimization problem is solved at each iteration for each of the filtered λ's:

$$\text{Min}\ \{\ \alpha,\ e^T(z^* - z)\}$$

$$\text{subject to} \qquad \alpha \geq \lambda_i(z^* - z), \quad 1 \leq i \leq k$$

$$f_i(x) = z_i$$

$$x \in S$$

where,

e^T is the unit vector

z^* is the ideal vector

α is an unrestricted dummy variable

S is the constraint set

The mathematical proof of this problem is provided in Steuer and Choo (1983), who have generalized the method for integer and non-linear problems. FORM, however, can currently deal only with linear problems and convex sets.

If the first stage minimization of α does not yield a nondominated criterion vector, the minimization of $e^T(z^* - z)$ is guaranteed to yield one that it is.

Let $z \in F$ be the nondominated criterion vector selected by the manager at the end of the first iteration. Considering that the $||z^* - z||^{\lambda}_{\infty}$ isoquant is positive, z defines this isoquant if and only if:

$$\lambda_i = \begin{cases} 1 & \text{if } z_i = z_i^* \\ \dfrac{1}{(z_i^* - z_i)} \left[\sum_{i=1}^{k} \dfrac{1}{(z_i^* - z_i)} \right]^{-1} & \text{if } z_i \neq z_i^* \text{ for all } i \\ 0 & \text{if } z_i \neq z_i^*, \text{ but } \exists\, j \text{ such that } z_j = z_j^* \end{cases}$$

These relationships are the necessary and sufficient conditions for **z** to be a nondominated criterion vector. The components of a λ weighting vector are set equal to 1 when the nondominated criterion vector and the ideal vector are equal. λ is set equal to 0 if the nondominated vector and the ideal vector have at least one identical element. λ is set equal to the mathematical quantity of the second row of λ_i, when the nondominated vector and the ideal vector are completely different.

Figure 3 shows the isoquant of the weighted L_∞-norm defined by a criterion vector **z**:

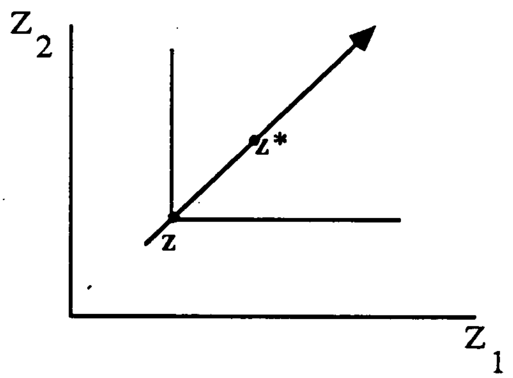


Figure 3
(Source: Steuer and Choo, 1983)

After the weighting vector $\lambda_i^{(h)}$ that has the selected criterion vector as the defining point of the weighted L_∞-norm isoquant, is defined, the lower and upper boundaries of the closed interval $[l_i, m_i]$ are computed. The weighting vectors λ_i at each iteration are drawn from this interval, which is sequentially smaller.

$$[l_i, m_i] = \begin{cases} [0, r^h] & \text{if } \lambda_i(h) - 1/2\ r^h \le 0 \\ [1-r^h, 1] & \text{if } \lambda_i(h) + 1/2\ r^h \ge 1 \\ [\lambda_i(h) - 1/2\ r^h, \lambda_i(h) + 1/2\ r^h] & \text{otherwise} \end{cases}$$

where, h denotes the iteration number and r the convergence factor. r^h implies r raised to the h^{th} power.

Let p be the sample size developed at each iteration and t the total number of iterations, that is the number of subsets of the nondominated solution set to be sampled. Each sample can be interpreted as a subset hypercube of the k-dimensional unit hypercube (k is the number of objectives), whose volume may be greater than or equal to 1/p. The convergence factor then would be $r \ge \sqrt[k]{1/p}$. It is believed that the final solution can be acquired from the sample of that iteration, whose $[l_i, m_i]$ width is less or equal to 1/q, that is within k number of iterations, therefore:

$$\sqrt[k]{1/p} \le r \le \sqrt[t-1]{1/q}$$

Steuer and Choo (1983), indicate that it suffices for q to be between 1/2k and 3/2k, but p should be no smaller than k. In the Queen Elizabeth Forest Park application with four objectives the optimal solution was obtained in the third iteration (see chapter 8).

The final step of the method involves computation of the inverse image of the final criterion vector chosen by the decision maker. The inverse image is defined as follows:

Let $N \subset F$, the set of all nondominated solutions, and **z** a nondominated criterion vector. An $x \in S$, where S is the constraint set, is said to be an efficient point, if and only if **x** is an inverse image of an $z \in N$. Let $E \subset S$ denote the set of all efficient points. A criterion vector $z^0 \in F$ is an optimal solution if z^0 maximizes the decision maker's utility function. This is mathematically unknown, but it is assumed that it is monotonically increasing. z^0 then is a nondominated vector, that is $z^0 \in N$. If $z^0 \in S$ is an inverse image of z^0, then x^0 is an efficient point ($x^0 \in E$) and consequently z^0 is an optimal solution of the multiple objective problem.

Summarizing the above discussion, the steps of the algorithm are as follows:

STEP 1. Specify the size of the sample (p) to be presented to the decision maker at each iteration, the number of iterations (t) and the convergence factor (r).

STEP 2. Maximize each objective function subject to the set of constraints.

Establish the ideal criterion vector, $z^* \in R^k$.

STEP 3. Set iteration number equal to zero [h = 0].

STEP 4. Increment iteration number [h = h + 1].

STEP 5. Generate randomly a large number of weighting vectors λ(e.g. 100Xk) from the closed interval [li,mi], such that

$$\lambda \in R^k, \quad \sum_{i=1}^{k} \lambda_i = 1.$$

If iteration equals 1 then $[l_i,m_i] = [0,1]$.

STEP 6. Reduce the set of weighting vectors λ using the filtering test with L_p=L_∞ to obtain a multiple of the specified sample size (e.g. 2 X p).

STEP 7. For each of the vectors of the filtered group solve the following lexicographic L_∞-norm weighted problem

$$\text{Min } \{ \alpha, \quad (z^* - z)\}$$

subject to

$$\alpha \geq \lambda_i(z_i^* - z_i), \quad 1 \leq i \leq k$$

$$f_i(x) = z_i$$

$$x \in S$$

STEP 8. Reduce the set of the nondominated criterion vectors using the filtering test with L_∞-norm to obtain a sample of specified size p.

STEP 9. Let $z^{(h)}$ the criterion vector selected as the most preferred by the decision maker in STEP 8.

STEP 10. Designate $\lambda^{(h)}$ the weighting vector which has $z^{(h)}$ as the defining point of a lexicographic weighted L_∞-norm isoquant, where,

$$\lambda_i^{(h)} = \begin{cases} 1 & \text{if } z_i^{(h)} = z_i^* \\ \dfrac{1}{(z_i^*-z_i^{(h)})} \left[\sum_{i=1}^{k} \dfrac{1}{(z_i^*-z_i^{(h)})} \right]^{-1} & \text{if } z_i^{(h)} \neq z_i^* \ \forall\, i \\ 0 & \text{if } z_i^{(h)} \neq z_i^*, \text{ but } \exists\, j, \\ & \text{such that } z_j^{(h)} = z_j^* \end{cases}$$

STEP 11. If h less than t GOTO STEP 14.

STEP 12. With $\boldsymbol{\lambda}^{(h)}$ being the weighting vector computed in STEP 10 define

$$[l_i, m_i] = \begin{cases} [0, r^h] & \text{if } \boldsymbol{\lambda}_i^{(h)} - 1/2r^h \leq 0 \\ [1-r^h, 1] & \text{if } \boldsymbol{\lambda}_i^{(h)} + 1/2r^h \geq 1 \\ [\boldsymbol{\lambda}_i^{(h)} - 1/2r^h, \boldsymbol{\lambda}_i^{(h)} + 1/2r^h] & \text{otherwise} \end{cases}$$

STEP 13. GOTO STEP 4.

STEP 14. Compute the inverse image of the decision maker's final criterion vector choice.

STEP 15. STOP.

In this chapter an attempt was made to illustrate the wide variety of multi-criteria methods which can be used to solve multi-objective forest management problems. However, all methods are not suitable for any forestry problem. The special characteristics of any case study must be examined before any investigation begins. The classification of MCDM methods presented in section 4.2 can be useful at the early stage of any such attempt. Most commonly a combination of approaches is proved appropriate. The MINIMAX combined approach described in section 4.3 was selected for the type of forest management problem under investigation and has been incorporated in FORM. The results of the application are presented in chapter 8.

CHAPTER FIVE. THE FRAMEWORK OF A DECISION SUPPORT SYSTEM (FORM) FOR FOREST RESOURCE ALLOCATIONS

5.1 INTRODUCTION

It has been argued in the literature, that decision analysis has not fulfilled its potential as a decision aid in the context of many applications (Ackoff, 1979a; Ackoff, 1979b; Eilon, 1980; Grayson, 1973; Brown, 1970). The main reason for this lies with the formulation and structure of the problem, rather than the strength of the decision analysis. Most of the problems, especially in the public sector, are ill structured, complex and have vaguely defined multiple objectives. Decision analysis can be valuable in such situations. This is because it can be viewed as a means of generating dialogue about problem formulation and available options, rather than as a means for identification of the optimal solution. This modified decision analysis approach is regarded as a support system for problem solving, rather than as an optimizing technique (Thomas and Samson, 1986).

Much controversy has developed since the early 70's with the 'decision support system (DSS)' term as to what DSS characteristics are sufficiently different to justify the term. Sprague and Carlson (1982) traced the cause to the difference between the theoretical definition and the 'connotational' definition of the term.

According to the 'connotational ' view, DSS is an evolutionary advancement in the electronic data processing (EDP)-management information systems (MIS) chain, beyond management information systems (MIS). EDP is mainly data focused (storage, processing, optimized computer runs and summary reports for management) applied to the lower operational levels of the organization. MIS is information oriented (structured information flows, production, marketing, personnel and report generation) applied to the middle level of management. DSS, finally, in the 'connotational' perspective are decision focused, user initiated and controlled. Their main emphasis is on flexibility, adaptability and quick response.

Theorists, however, have pointed out serious deficiencies in this definition and characterized it the 'narrow' view of the term. Decision support is not needed only at the top management as the'connotational' definition implies. Indeed, an important dimension of decision support is co-ordination of decision-making across all levels of management. Decision support is not the only thing managers need from an information system, because decision-making is only one of their activities they benefit from information systems support. DSS, therefore, are a class of information systems, which are based on transaction processing systems and interact with the other parts of the overall information system to support the decision-making activities of

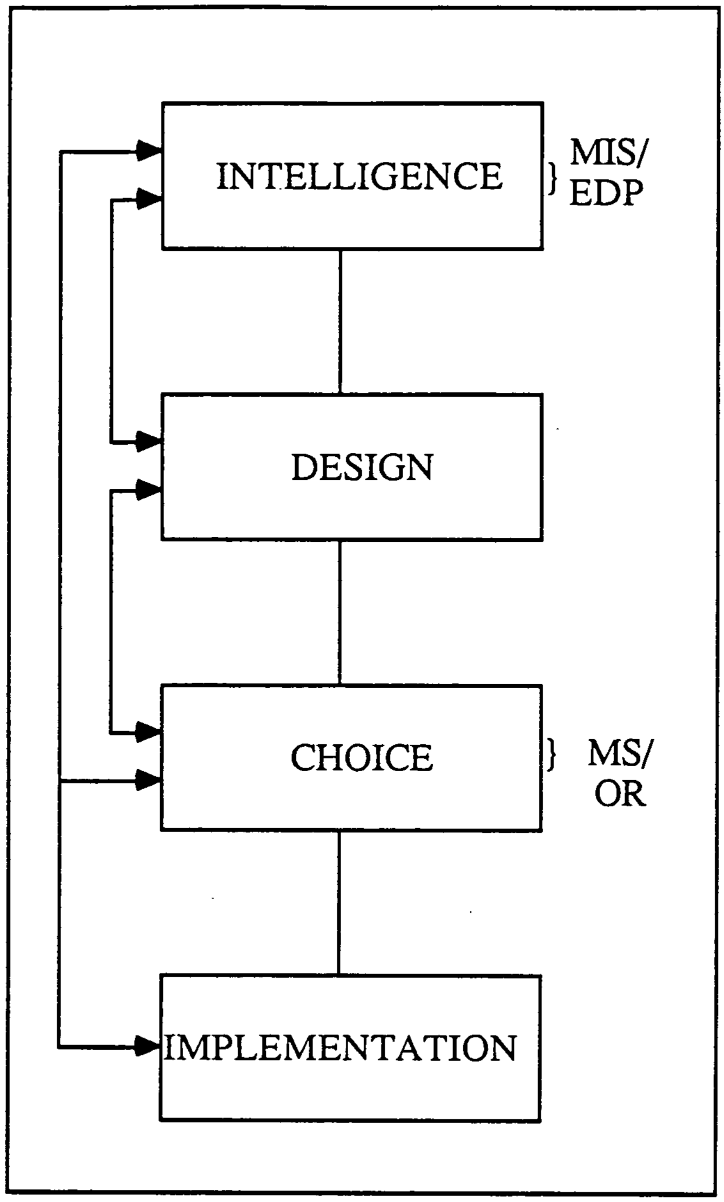


Figure 4. Sequence and Interaction Phases of Decision-Making in a Decision Support System (DSS)
(Source: Sprague and Carlson, 1982)

Legend:
MIS: Management Information Systems
EDP: Electronic Data Processing
MS: Management Science
OR: Operations Research

managers and other workers in organizations.

In any case, three levels of technology have been designated DSS:

* Specific DSS, which are the hardware/software that allow a specific decision maker to deal with specific sets of related problems.

* DSS generators, which are packages of hardware/software that provide a set of capabilities to build specific DSS quickly.

* DSS tools, which are hardware/software elements which facilitate the development of specific DSS of DSS generators.

Specific DSS can be developed directly from tools or from a DSS generator. The direct approach is less flexible in incorporating change, since the nature of a specific DSS depends on the nature of the problem, the user's approach to the problem and the environment within which the user faces the problem.

The performance objectives that a DSS should satisfy are the following:

-It should provide support for decision-making, with emphasis on hard or underspecified decision problems.

-It should provide decision-making support for users at all levels, assisting in integration between the levels whenever appropriate.

-It should support decisions that are interdependent as well as those that are independent.

-It should support all phases of decision-making. These are shown in Figure 4.

The diagram is cited in Sprague and Carlson (1982), but it was originated by Simon (1960). Intelligence refers to identification and structure of the problem by searching a specific environment for conditions calling for decisions, collection and processing of raw data. Design includes development and analysis of alternative courses of action. Choice involves selection of a particular alternative from those available. Implementation follows, after a choice is made. Interaction occurs between all phases of the decision-making process. Design, Choice and Implementation phases depend on Intelligence. Feedback loops are allowed between Design and Intelligence and between Design and Choice stages. Finally Implementation may lead to re-structuring of the problem. It has to be made clear at this point, however, that these stages of decision-making do not constitute a general framework of the decision-making process. This is almost impossible due to the variable character of decisions and decision makers. However, these stages have been identified for decision-making in multi-objective public forest management and have constituted the build-up phases of FORM.

-It should be process independent and user controlled and, finally,

-It should be easy to use. This attribute implies flexibility and 'user friendliness'.

The following two sections of this chapter include a general description of FORM and description of the subject area which served as basis for its developement.

5.2 GENERAL DESCRIPTION OF FORM

FORM (FORest Management) is a decision support system generator for resource allocation in public forests which are managed for multiple objectives.

Resource allocation is a tactical planning problem facing the forest managers of public forests at the forest district level.

The system is characterized by strong elements of subjectivity. Indeed the process of generating alternatives requires some experience on the part of the forest manager and is more efficiently supported through use of computers. Subjective judgement are facilitated through analytic information supplied by the computer as well as graphics.

From the user's point of view FORM provides support for manipulating data related to different forest habitats in the forest. The particular type of decision involves design of a set of habitats managed under different regimes to meet certain requirements over multiple time periods. The decision involves considering factors, such as:

* Establishment of management requirements.
* Potential of different habitats for a particular management objective under different regimes over time.
* Balancing of the distribution of habitats to meet the specified requirements.

A diagrammatic presentation of FORM from the user's point of view is shown in Figure 5.

Four components can be recognized. The first (intelligence), refers to problem formulation and includes identification of objectives, constraints, alternative regimes, habitat types and models with respect to the objectives.

The second (design), uses the outputs of the first component in a technological forecast model and produces technical coefficients(input-output functions).

The third component uses a multi-objective optimization procedure, which results iteratively in trade-off outputs. The input-output functions and the trade-off outputs can be presented in tabular and/or graphical form.

The fourth component (implementation) includes the final resource allocation scheme adopted after examining trade-offs.

The decision-making process regulates the system in part three by comparing the achieved targets with the specified goals in part one and allows for corrective action in pursuit of the required goals. A feedback process also from part three to part one allows for restructuring of the problem.

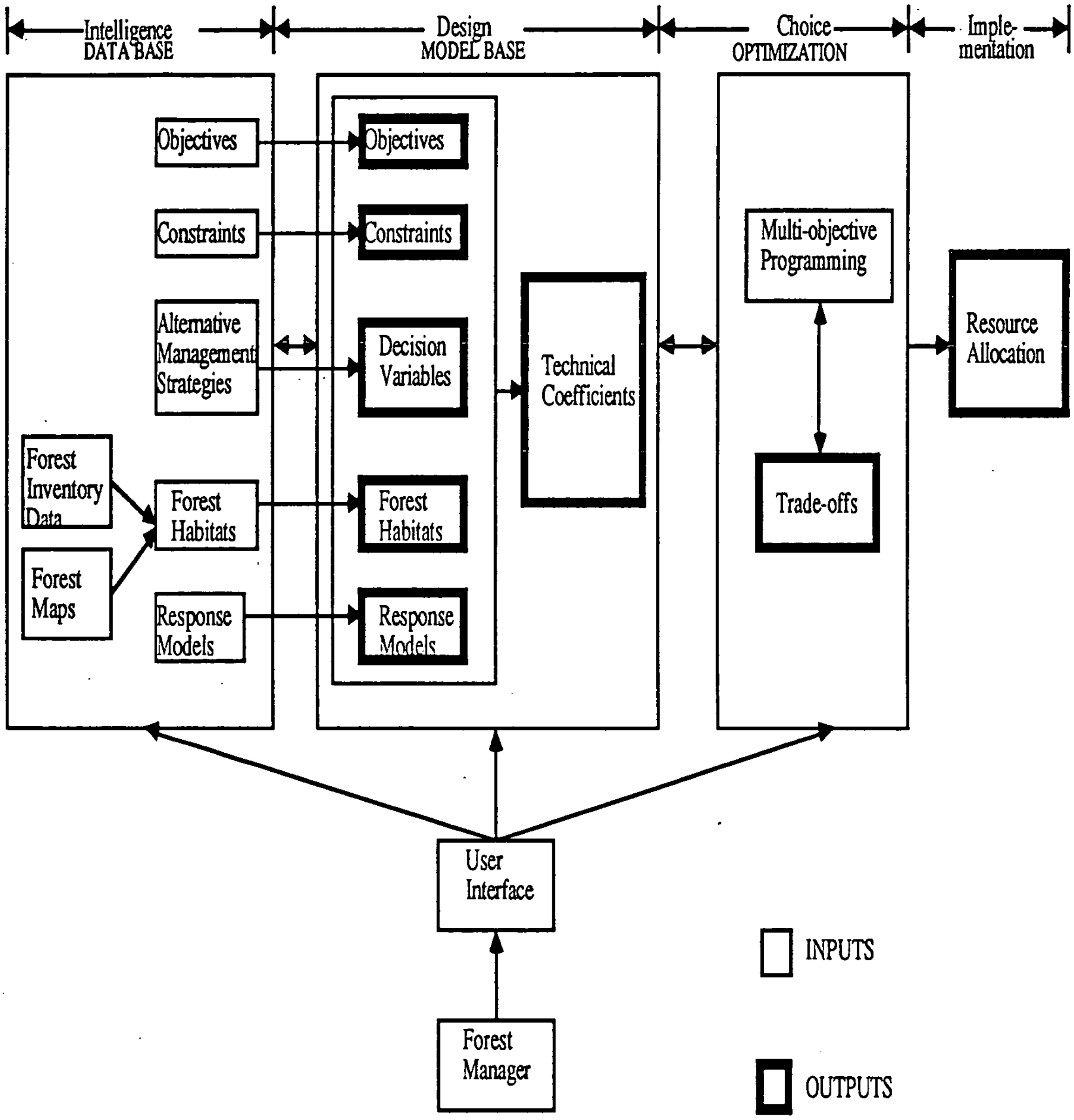


Figure 5. The user's view of FORM

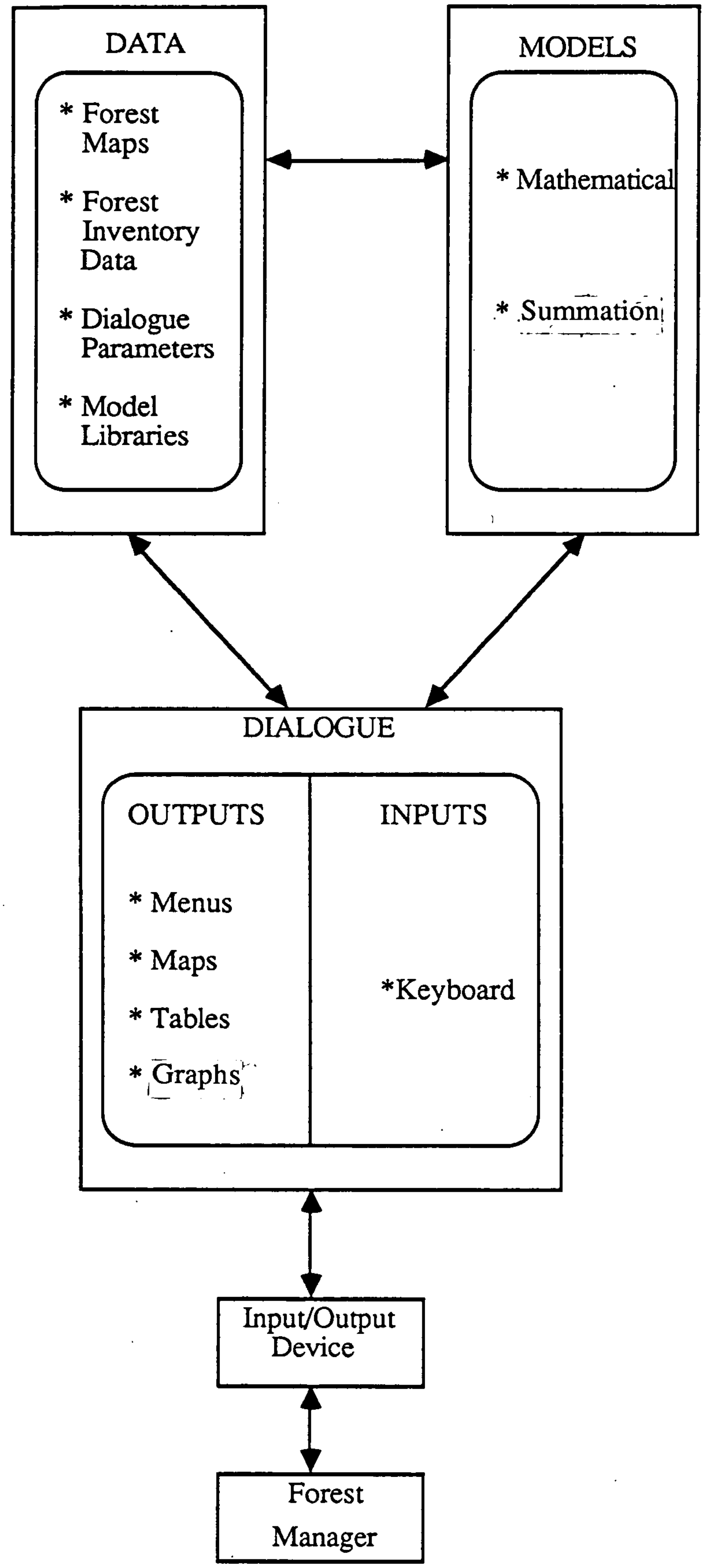


Figure 6. The builder's view of FORM

A diagrammatic presentation of FORM from the builder's point of view is shown in Figure 6.

The data base includes:

* Forest stock maps
* Forest inventory subcompartment data file
* Dialogue parameters and
* Model libraries

The model base consists of two types of functions:

* Arithmetic and
* Summation

The dialogue part requires a keyboard to input information, and also provides menus, maps, tables and graphics for display of the output information.

Finally, the optimization component includes, at present, a combined approach based on the MINIMAX concept.

5.3 SUBJECT AREA

Although FORM is a DSS generator and can be used in most British forests, a study area was necessary for its development, since forest management is a function of spatial characteristics and time.

The Queen Elizabeth Forest Park was selected for reasons which are outlined in the following paragraphs.

The Park is a mixed public forest managed for multiple objectives. It forms part of Aberfoyle Forest District and consists of three forest blocks: Achray Forest, Loch Ard Forest and Rowardennan Forest (Forestry Commission, 1951,1961,1973). It combines a wide variety of habitats and a rich diversity of scenery, stretching from Loch Venachar and the headwaters of the Forth over the summit of Ben Lomond to the shores of Loch Lomond (see Figure 7). Its area extent is approximately 18,000 hectares of which 10,000 hectares are covered by forest, while the rest of it consists of moor and mountainside.

The Park lies within easy reach of large urban centres (Glasgow, Edinburgh, Stirling), thus making the recreation input to the area a considerable factor in its management.

The summer annual average recreational usage of the Park has been estimated by the Aberfoyle forest District staff (1985) to 150,000 visitors (unpublished report). The management of the Park provides a number of recreational facilities, mainly for day visitors on foot, conveniently located throughout the Park to cover most of the needs of the visitors. Car parks have been situated on the fringes of the forests and waymarked footpaths lead the visitors to various sites within the forests and up to the mountain tops. There are two camping/caravan sites and twelve small camping areas for youth organizations, a wayfaring course, picnic places and a scenic drive (see recreation pocket map).

Interpretation facilities are provided through a visitor centre, the David Marshall Lodge. This is located near Aberfoyle, which is a picturesque village in the Trossachs area used mainly as a basis for exploring the Park. The Forest District Office is also based in Aberfoyle.

People can get involved in a wide range of recreational activities,both land- and water-based. Water is the most striking element of the scenery, which along with the topography of the area and the vegetation enriches the variety of form, texture and colour. Swimming, fishing, canoeing, boating and sailing are amongst the most popular water-based activities, especially in the Loch Lomond, which lies next to Rowardennan Forest. The Park supports a variety of birds and mammals, while numerous species of fish are found in rivers, streams and lochs within the Park. One of the most popular activities connected to the wildlife of the Park is deer stalking. This sporting activity is of importance because of the thriving population of the deer species , which have a considerable impact on the forest plantations. Shooting is a means of regulating the population. It is subject to ecological considerations and brings a significant income to the Forestry Commission, which owns the Park.

The Park is considered of high conservation value mainly due to variation and complex interaction between geology, landform, climate and biological action. It supports a diversity and richness of wildlife habitats and animal and plant communities.

Geologically the underlying rocks of the Park belong to the Dalradian series. This series is characterized as typical metamorphic rocks. This type has resulted over the years through compaction, compression and high temperatures of gravels,sands and muds, which was the original constitution of the Dalriadian series. The main geological and landform feature, however, is the Highland Boundary Fault. This separates the Old Red Sandstone to the south from the Dalriadian rocks to the north, splitting the Park into the characteristic Highlands and Lowlands of Scotland. The most striking effect of this geological formation is reflected in the chemical composition and acidity of the water courses. Those below the fault line contain fish, while those above are fishless.

A rich variety of woodland types occur including northern-and southern-type oakwoods. The number of ancient deciduous woodlands is amongst the highest in Scotland. The management of the Park is oriented towards conservation measures aimed at improving the woodlands as wildlife habitats in relation to forest operations.

These include plant and structural diversity and site management considerations.

Plant diversity is attempted through retention of a variety of trees and shrubs. Broadleaved species are encouraged either by maintaining scattered individuals or blocks or new planting.

Structural diversity is aimed at through planting of mixed blocks to generate a range of age classes. There is a management intention also to create relatively large broadleaved continuous areas rather than small scattered groups.

The site management considerations are related to specific conservation sites throughout the forest. For example, overmature scattered trees are retained, because they provide a favourable habitat for birds. Broadleaved trees are planted along the paths, rides, roads and around lakes to promote structural and species diversity. Fertilization and use of pesticides is avoided in specific rich habitats of high conservation value.

Wood production, however, remains the primary objective of the management of the Park. Planned forestry has been practised in the valley of Loch Chon and Loch Ard since the eighteenth century. Broadleaved woodlands mainly of oak, birch and ash were managed on a 'coppice-with standards' system. Forest products were then oak bark for the extraction of tannin, building and fencing materials, and wood for fuel. Planned forestry continued throughout the nineteenth century.

After the Forestry Commission's formation in 1919 more land was acquired and establishment of plantations started in 1930.

To date management has brought an even distribution of age-classes in the forest blocks of the Park. Sitka spruce is the predominant species forming the bulk of the commercial timber crop. Other important commercial species include Norway Spruce, Scots Pine, Lodgepole Pine, Larch and Douglas Fir.

The time of thinning and clear-felling is determined by the yield capacity of the site and the cultural regime is applied throughout the life of the crop.

The average volume production is approximately 70,000 m^3 per year, but there is a lot more potential as the fast-growing conifers approach their optimum felling age. About one third of the total production is sold standing, while the rest is worked by Forestry Commission through its own labour and direct contractors for sale at the roadside. Harvesting systems are both motor and manual, while the road network throughout the forest is good.

It becomes clear from the preceding paragraphs that the management of the Park has to accommodate multiple objectives trying to make the most of the available resources of the Park over time. Therefore, it was considered very suitable to serve as basis for the development of FORM, since it is believed that its management objectives would also be similar to the objectives of most of the other British national forest parks.

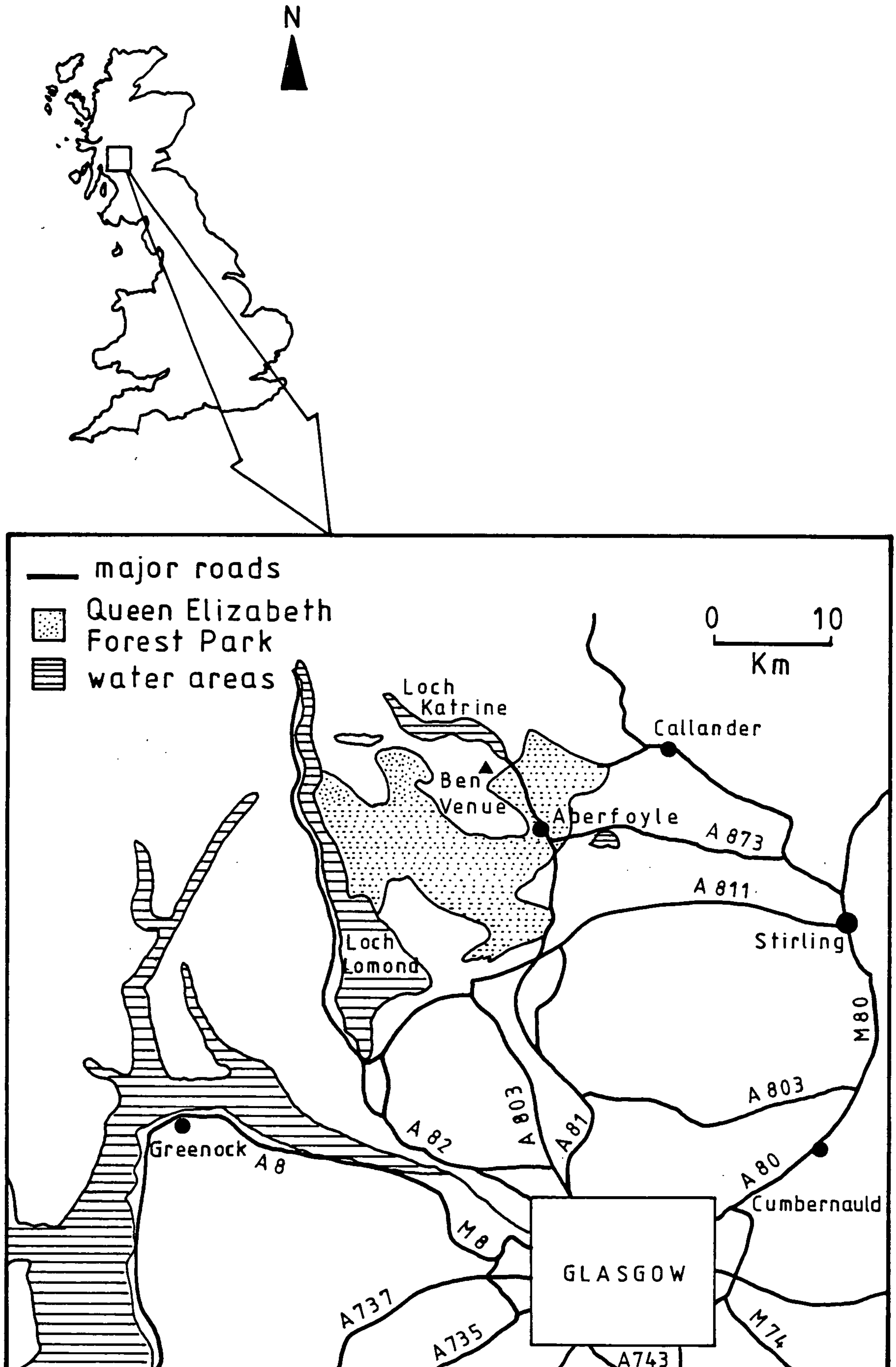


Figure 7. Location Map of the Queen Elizabeth Forest Park

CHAPTER SIX. DATA BASE OF FORM- INTELLIGENCE PHASE

6.1 INTRODUCTION

In chapter five the general framework of FORM was presented. This chapter deals with the first component of FORM, that is the data base of the decision support system or in other words the intelligence phase of the decision-making process. The data base relates to the formulation of the problem, that is all these elements which are required to frame the managerial environment and structure the decision-making context.

The chapter is organized in six sections. Section 6.2 describes identification and formulation procedures of forest management objectives. Section 6.3 refers to forest management constraints which are the resource requirements. Section 6.4 defines forest management alternative strategies, as they are related to resource requirements and forest management objectives. Section 6.5 refers to the formation procedure of forest habitat types, while finally section 6.6 pertains to the necessity of developing forest model libraries.

6.2 FOREST MANAGEMENT OBJECTIVES

The FORM decision support data base begins with identification and formulation of objectives. The concept of objective in any management context (including forest management) is strongly related to the concept of value, which is of key importance to Economics.

Some controversy has been brought forward in the literature regarding the definition of the term. Hill (1973) defined an objective as an 'ideal', that is a general evaluative statement with which almost all people would agree. Other authors (Cohon, 1978; Zeleny, 1982) base the definition of an objective in operational usefulness. According to them, an objective is an operationally useful statement, which is consistent with an underlying ideal, but with which not all people necessarily agree. It can be expressed as a mathematical function involving decision variables and represents a direction of improvement (minimum or maximum) along attributes.

The 'operational' definition allows for quantification of objectives, while the 'ideal' one does not. For example, tree volume is an attribute of the forest and maximization of tree volume is an objective, while maximization of social welfare (which may include maximization of tree volume) is an ideal and can not be quantified. Other terms, which are used synonymously for objectives include 'goals' and 'criteria'. A goal is an objective with a priori specified level of achievement attached to it. Criteria is a more general term and involves objectives or goals, which have been specified in a given decision situation by a decision maker or a group of decision makers.

The identification process of objective(s) is generally difficult and deserves some attention. In an industrial firm, the decision maker is usually able to identify management objectives more easily than the decision maker in the public sector. Difficulties increase with the size and complexity of the problem, the degree of variety of products and services and their importance to consumers and finally the complexity of the owning body.

There are, however, a few mechanisms which can be used in the identification process. A research review of the history of the problem, as well as potential conflicts, may be a valuable source to reveal patterns of social wants, which have to be incorporated in the system. This must be done with care, as human wants change according to cultural patterns and psychological conditioning. Another source may be official documents, such as published governmental policy material. A potential pitfall with respect to this source is that public documents may not include the whole range of issues necessary to incorporate in the decision-making process. A better source, although more time consuming, is surveys. These, if well organized, display representative patterns of social needs.

The identification process should be followed by a quantification process with respect to decision variables (see section 6.3) for the decision analysis to proceed. Quantification regards mathematical formulation of the objective statements. Generalizations, however, can not be made for this process because objectives are problem specific.

In the forest management context identification of objectives is easier than in other public management environments. This can be attributed to the following two reasons: First, almost all forest decision makers , especially in Europe, have been educated with the 'forest ideal'. This states that the basic purpose of forest management should be to secure the greatest continued value from the forest land to the greatest number of people (Knuchel, 1953; Brasnett, 1953; Osmaston, 1968). Second, there is usually much published material, in each country, about the value of forests and forest policy lines which have to be pursued through the management of forests.

Generally, objectives in public forest management can be extracted from knowledge of the values (products and services) forestry offers from use of land. These can be summarized as follows:

* Production of material forest goods. These include a wide array of products from major such as wooden products, to minor such as resin, fruits and grass. Quantification of these products is straightforward. Measurement can be made either in physical units, for example m^3 of volume, or in money.

* Provision of service goods. These include:

a) Protective and regulative services. Such services are achieved through i) the form, bulk and roots of trees ii) transpiration process and iii) enrichment of soil through the decaying litter from leaves and branches.

The form, bulk and root network of forest tree species make forests controllers of land and snow slips or soil erosion. In many cases forests even prevent soil erosion from occurring. The more continuous the canopy remains, the more protective their function is. In forestry practice, this is achieved through regulation of fellings, that is using smaller size interspersed felling coupes.

Through the transpiration process and decaying vegetative litter, forests affect the disposal of precipitation. Forests, due to their high rates of evapotranspiration, reduce the flow of water through the landscape. By intercepting rainfall, storing water in plant tissues and building absorptive soils, they reduce run-off and by delay regulate the water-flow to water courses. Harvest increases the total streamflow the first year. Flows, however, decrease during the seedling stage and return to the levels before harvest, in the beginning of the sapling stage (Douglass and Swank, 1972; Douglass, 1974). Forests also delay the flow of nutrients through the landscape, but it is not known yet how much these delays are reduced by the removal of trees.

b) Socio-cultural services. These are related to social benefits derived from forests. The most important are: employment either through use of labour in forests themselves or in industries which are dependent on forests, recreation, amenity and scientific study. Forests are also valuable habitats for numerous animal species.

Identification of objectives derived from service functions of forests therefore, seems readily attainable. They can be expressed as minimization of soil erosion, maximization of habitats which support animal species or maximization of labour used in forests. However, the thorny area of forest decision analysis is the quantification of these objectives with regard to decision variables, which usually involve silvicultural and operational treatments.

Attemps to quantify objectives in forest valuation studies so far, have mainly included approaches which convert physical or other units in money value. Multi-criteria decision-making techniques allow each objective to be considered in its own terms. For example, recreation from the management point of view can be quantified in terms of visitor days which can be accommodated in different forest habitats. Wildlife conservation can be viewed in terms of potential index schemes of forest habitats ranging from rich habitats to poor habitats for various wildlife species. It has to be stressed, however, that quantification procedures of this type are very difficult in forest management as they are time consuming. FORM revealed many areas where such research is required.

For resource allocation in the Queen Elizabeth Forest Park solved with FORM, only the following four objectives were considered mainly due to lack of habitat models and appropriate quantification for other objectives.

1. Minimization of the timber yield surplus (overdeviation from goal target)
2. Minimization of the dispersed recreation surplus (overdeviation from goal target)
3. Minimization of the water-based recreation surplus (overdeviation from goal target)
4. Minimization of the deer stalking surplus (overdeviation from goal target)

The objectives were extracted from official published material about the forest and consultation with the district forest manager. Recreation was considered as two separate items, because of the different relationship between user-requirements and resource requirements. Deer stalking was viewed from the sport aspect. Wood volume (m^3) was selected as the unit measurement for the timber production objective, while visitor days and shooting days were the units used for the two recreation and the deer stalking objectives respectively. 1 visitor day is defined as the amount of time spent by 1 visitor in the forest for recreation on a 12-hour basis. 1 shooting day is the amount of time spent by 1 stalker in the forest on a 12- hour basis.

6.3 FOREST MANAGEMENT CONSTRAINTS

The allocation of resources between alternative means of action in order to produce a number of goods or provide a number of services is a matter of the relative urgency of demands for these goods or services, their relative production cost and the impact their production processes have on the environment.

In meeting increased levels of demand forest management is forced towards higher productivity, since resources are not unlimited. This usually results in negative impacts on the forest environment and therefore calls for setting up of limits regarding resource requirements. Resources refer to the agents that go in the production of forest goods and services, that is land, capital and labour. In this context, identification and quantification of constraints, which is the second part of the FORM decision support data base implies formulation of functional relationships, which express resource requirements in relation to the decision variables. In some problem formulations constraints can not be violated.

Resource requirements of the land factor of production are related to physical characteristics of land, that is its quantity and quality. Quantity refers to the physical boundaries of forest land as determined by ownership. Quality of a given unit of forest land refers to attributes, such as altitude, topography, composition of the surface and subsurface and geographical location relative to other units of resources and to economic activities. These attributes result in a wide variation in productivity from one land type to another. They also generate a different potential for provision of services, such as recreation, aesthetics and wildlife conservation.

Capital is required in management in two forms: operational (working capital) and fixed. Working capital is used in forest management in the same context as in any business management, that is in the form of money to meet raw material purchases and acquisition of supplies. Capital in the form of growing stock is associated with sustained yield constraints. These include any forest outputs, tangible (wood and other material forest products) and intangible (forest services). Most often, however, sustained yield constraints in forest management are evolved around timber capital. This does not imply that the value of sustention of the other products and services is less important. These other products and services are to a big extent functionally related to the distribution of age classes of forest tree species.

Maximum sustained yield is generally defined as the regular continuous supply of the desired output to the full capacity of the forest (Osmaston, 1968). For wood there are three different ways of collecting sustained yields: i) Integral yields, when the whole forest consists of one age of tree and is felled and replanted at one time, for example every 60 years. ii) Intermittent yields, when the forest includes several age classes of tree, so that timber is harvestable at regular intervals of several years. iii) Annual yields, when mature timber is available for felling every year. In most cases, sustained production is understood as regular annual yields.

In developed countries two economic arguments have been debated about the necessity of regular annual sustained yields. The first states that a regulation of this type offers no flexibility regarding modification of production to suit demand, so that felling can not be increased during time of high prices, nor reduced for low prices. This consequently may result in market destabilization by forcing high prices still higher and low prices to fall yet more. However, this can be overcome by regulating yields over a period of years, rather than annually. The second argument is more serious. To sustain yields on a rigid regular annual basis requires sustention of trees of different ages and sizes in proportions, which secure a regular sequence of mature timber. This can only be achieved by harvesting stands either earlier or after the financially optimum time, which from the pure profit-making point of view is not desirable.

Despite these arguments forest management of small private forests is more efficient, when operating on an annual sustained basis, because planning of resources, especially labour and working capital, can be better organized. Public forest management in developed countries would suffice to operate on regional sustained yield over a period of years, because the overall aim of state forestry is general welfare and wealth. In Britain, however, the opposite is true. The state forests are commited to regular annual supply in order to cover market demands. Private forests are not so commited generally. British state forest management has adopted a general scheme for felling at financially optimal ages. Nevertheless, retentions are made in many forests for recreation and conservation purposes.

Labour requirements are variable and affect production cost. They result in operational constraints, associated with the working capital available. When labour supply is large, public forest management is forced in adopting ways, which absorb a great deal of the supply.

In the Queen Elizabeth Forest Park case study, the following types of constraints were considered, which were thought as typical of British forest parks management :

* Land constraints defined by the physical boundaries of the forest area, measured in ha of land.

* A budget constraint, associated with the average cost per year per ha of each decision variable, measured in £ sterling.

* Nature conservation constraints defined by ha of land which has either to be retained or planted with broadleaves over time, measured in ha of land.

* Timber constraints defined by a certain volume of timber which has to be produced at regular time intervals, measured in m^3.

* Dispersed recreation constraints defined by the number of visitor days which can be accommodated in the forest over time, measured in visitor days.

* Water-based recreation constraints defined by the number of visitor days which can be accommodated in the forest over time, measured in visitor days.

* Deer stalking constraints defined by the number of shooting days which can be accommodated in the forest over time, measured in shooting days.

6.4 FOREST MANAGEMENT ALTERNATIVE STRATEGIES

After the objectives and constraints of the managerial environment are identified and quantified, alternative courses of action, that is means of achieving the objectives have to be specified. These alternative courses of action constitute the decision variables of the resource allocation problem.

Although the decision variables, like the objectives and constraints, are problem specific, in managing a particular forest there is scope for some generalization. At the district forest level, the means of achieving forest management objectives, are different forest management strategies, each expressed as a unique time function of silvicultural and harvesting actions applied through a specified rotation.

Silvicultural activities usually involve ground preparation, ploughing, planting, beating up, weeding, cleaning, brashing and fertilizing.

Harvesting activities include thinnings at specified time intervals and clearfelling at the financially optimum felling age or at the age of maximum mean annual increment.

In British public forests, a range of alternative strategies can be developed between two extremes: the marginal thinning strategy (MT) and the non-thinning strategy (NT). The first involves some or all silvicultural activities mentioned before, thinnings at 5-year intervals at the marginal thinning intensity, which involves removal of 70% of the yield class and clearfelling at the financially optimum age. The second involves no thinnings, but only clearfelling at the optimum felling age. In FORM, 5 more options are considered, between these two extremes:

* Marginal thinning with delayed first age of thinnings by 10 years (D10).
* Marginal thinning with delayed first age of thinnings by 5 years (D5).
* Marginal thinning with extended rotation by 5 years beyond the optimum felling age (EXR5).
* Marginal thinning with extended rotation by 10 years beyond the optimum felling age (EXR10).
* Marginal thinning with extended rotation by 15 years beyond the optimum felling age (EXR15).

Theoretically, a very large number of feasible alternative combinations can be generated, when associating these options with different habitat types. In addition the data associated with these options vary according to different spacings between tree species causing a great difficulty with regard to computer storage requirements. Practically, however, the number of feasible alternatives can be reduced by aggregating habitat types (section 6.5).

6.5 FOREST HABITAT TYPES

Forest management is concerned with spatial and temporal organization and conduct of all operations, which are needed to fulfil the objectives of the owner or the owning body. Any attempt, therefore, to develop a decision support system for forest management should incorporate space as well as time dimensions.

Managing a forest for multiple purposes (marketable and/or non-marketable) requires identification of different habitats of the forest environment. Habitat in this context denotes a specific land use or crop type within the forest. The reason for a distinction lies in the different resource potential of forest cover types for various benefits. However, the dynamic nature of forest ecosystems involves great difficulty in handling both spatial and temporal information. Computer-based procedures could help overcome the problem by providing flexibility in manipulating this information.

The FORM data base includes a computerized procedure for forest habitat mapping. Two functions can be recognized within this procedure: computer forest mapping and a structure for processing the spatial data base.

Data input for the computer forest mapping encompasses forest stock maps on a scale 1:25,000 and the Forestry Commission inventory subcompartment data base.

A forest stock map of a particular forest is a composite map, which shows the boundaries of the forest compartments and within these, the area of each subcompartment, its tree species and planting year as well as the road network and water features; in Geographic Information Systems terminology these are called 'themes'.

Division of forests in compartments and subcompartments has been established conventionally to facilitate management. A forest compartment can be defined as the smallest subdivision of a forest having permanently and clearly defined boundaries, used mainly for the purpose of location. A forest subcompartment is the smallest management unit in a forest. Forest subcompartments have no permanent boundaries due to management and natural intervention and are used for description, prescription, record and control.

The Forestry Commission subcompartment data base is a computerized data base in standard format, which contains information on each component (element of a mixed crop or land use, within a subcompartment) by subcompartment (Horne, 1984; Horne and Whitlock, 1984). Data on all Forestry Commission land are held in files by Forest District, in three fields: 1) The key field, which contains location information by Forest District, geographical block, compartment, subcompartment and component. 2) The required data field, which provides crop data, such as land use and crop type, storey, species, planting year, yield class, area and local authority area. 3) The optional data field containing site factors , such as soil type, altitude, terrain type and wind hazard class. Forest District Managers are responsible for updating the data annually. A validation program is run after any corrections are made and amendment of master files follows. The data base is fully revised by the Field Survey Branch following survey every 15 years.

Forest stock maps provide a static view of the forest, since they are issued at the year of the survey and updated every 10 or 15 years. The FORM forest mapping data base is dynamic in the sense that it can be updated annually following the subcompartment data base updating, which is related to the forest operations of felling and replanting or new planting.

Each cartographic location in this computer forest mapping data base is related to one thematic attribute, .i.e. crop type or land use. Each attribute is represented by a name (label), for example, 'water area' and a value. An imaginary grid pattern over the study area (shown on stock maps) was established and values identifying the attribute at each grid space were stored. This type of storage of the location information is called raster (square grid cell). This simply means that information is stored in the interior of regions. The other alternative would be the polygon (or line segment) approach (Berry, 1987), which stores information about the boundaries between regions.

All compartments are defined with respect to a cartographic grid of numbered rows and columns. The smallest addressable unit of space corresponds to a square parcel of land or in formal terms a'point'. Spatial patterns are represented by assigning a value to all points within a particular region for each parameter of study.

The processing structure involves generation of one map at each run from the data file, whose regions are represented by attribute values formed on a point by point basis using logical combinations. The forest manager is able to decide on the formation of habitat units, which he can use as treatment blocks by searching different spatial combinations of various productive tree species, non-productive species, unplantable land, agricultural land and/or water areas.

The processing spatial data program (FORM_HATMAP) allows for three logical conditions, 'OR' = 1, 'AND' = 2, and 'ONLY' = 3. When 1 is selected by the forest manager for a certain number of species or a specific land use, the generated map will display the areas which will satisfy both features. Choice 2 generates the areas which contain the specified combination of species or land uses exclusively. The same type of function is performed by choice 3, but only one crop type or land use in each grid square can be searched. Therefore, condition 1 is 'type inclusive', while conditions 2 and 3 are 'type exclusive'.

Some examples are shown in figures 8 to 11. On figure 8 the forest manager is assumed to be searching for three habitat types: area of spruces, agricultural land and 'other land'. The logical operand in all three choices is 3. On figure 9 a search is assumed for another three habitat types, namely: pines, spruces/larches and 'other land' with logical operands 3, 2, 2 respectively. On figure 10 two searches are assumed, mixed conifers with condition 1 and conifers/broadleaves habitat with condition 3.

The program runs on the EMAS system (IBM 370-XA mainframe computer) and can be accessed either through BBC with XTALK emulator micros or TEKTRONIX 4010. The DRAWPICTURE software can be used to view the maps, before sending the output to a plotter device. The source language of the program is EDINBURGH FORTRAN and the graphical routines belong to the GRAPHPACK software of the EUCC (Edinburgh University Computing Service). Output can be obtained from the CALCOMP 936 printer.

The map on figure 11 shows the pattern of habitat types, which has formed the basis for the Queen Elizabeth case study. This pattern consists of 5 types all based on condition 3: 1) spruces 2) spruces/pines/larches 3) mixed conifers 4) conifers/broadleaves 5) other land. The 'other land' type includes open land, land with individual trees or small blocks of trees, agricultural land and moorland. One more habitat type was considered in the case study, the overmature habitat. This consists of all subcompartments throughout the forest , which contain all tree species left unharvested beyond their optimum felling ages. This type is not shown on the map. The reason for this is that another data base with age classes as thematic attribute was required, which was not possible to build with the time constraints of this project. However, such a data base can be added at a later stage, as a further extention to the system. Based on this differentiation of forest habitat types a program (FORM_PROGUNS) was written in FORTRAN77 to generate different files, each containing all subcompartments throughout the forest, which belong to each of the specified habitat type. FORM_PROGUNS uses the subcompartment data base as input data base.

6.6 FOREST MODEL LIBRARIES

Model libraries include two types of data: primary and secondary. Primary data are those collected at first hand through surveys, research and experimentation. Experimentation may be either on a model of the system or the system itself. For example, a yield model can be used to decide upon the volume expected on replanting with a certain species, instead of carrying out an experiment on the actual site. Secondary data are those made available through the work of others.

In Chapter 3 a number of forest model libraries presently incorporated in FORM have been presented. From these the volume data and the deer stalking data are secondary, although they have been processed to suit better the multi-period forest management problem. The recreation data (dispersed and water-based) are primary and have resulted from a survey carried out in the forest. These forest model libraries have been integrated in FORM_CFGENS to produce input-output relationships of forest products and services (see chapter 7). There is need, however, to elaborate the existing models and also develop forest models of this type for more products and services more realistically to represent the multi-objective forest resource allocation problem. Forest managers would therefore, gain more confidence in respect of solutions suggested by decision support systems.

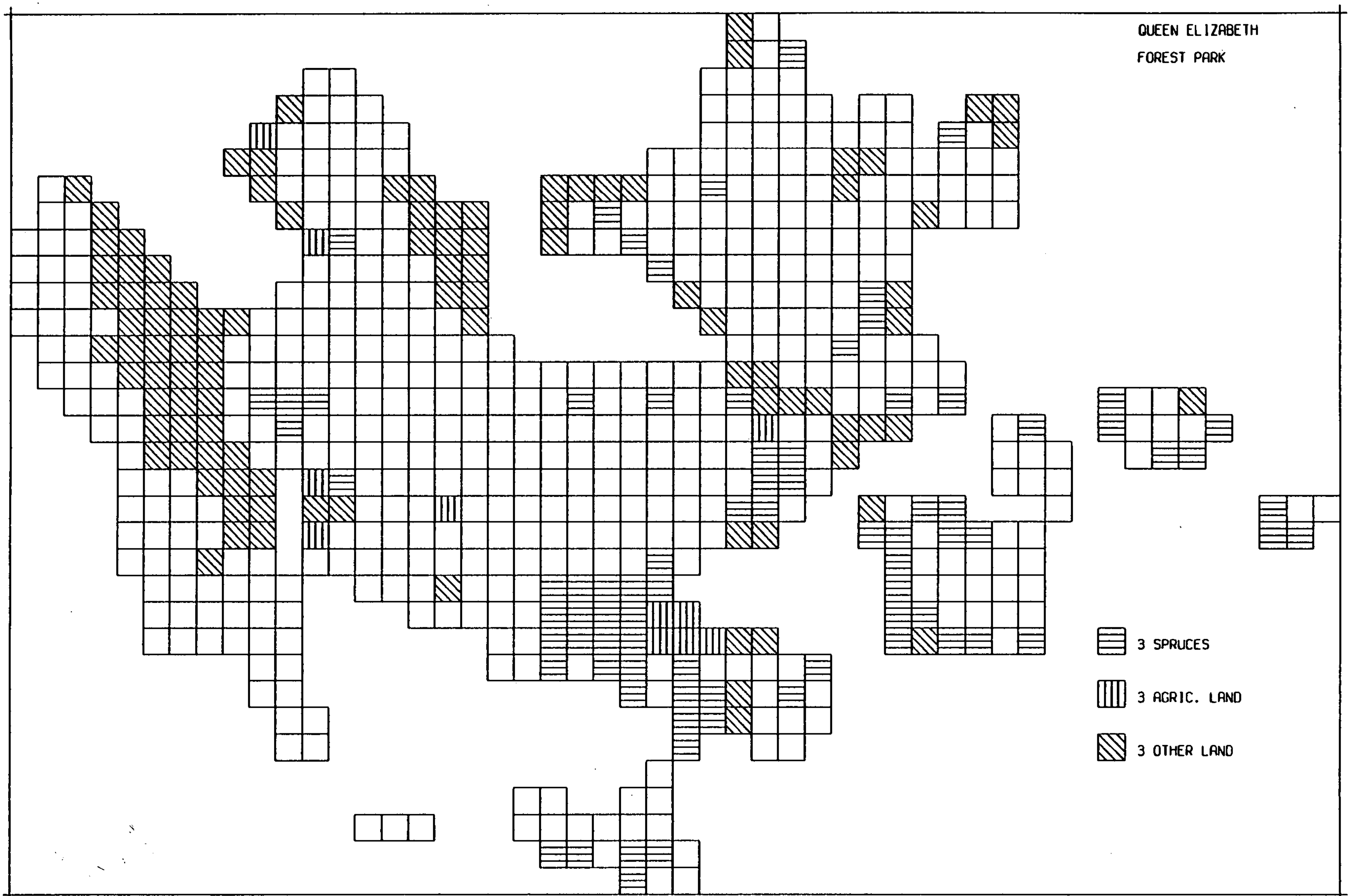


Figure 8. Tentative run of FORM_MAP for the Queen Elizabeth Forest Park.
A search for three habitat types: spruces-agric. land-other land

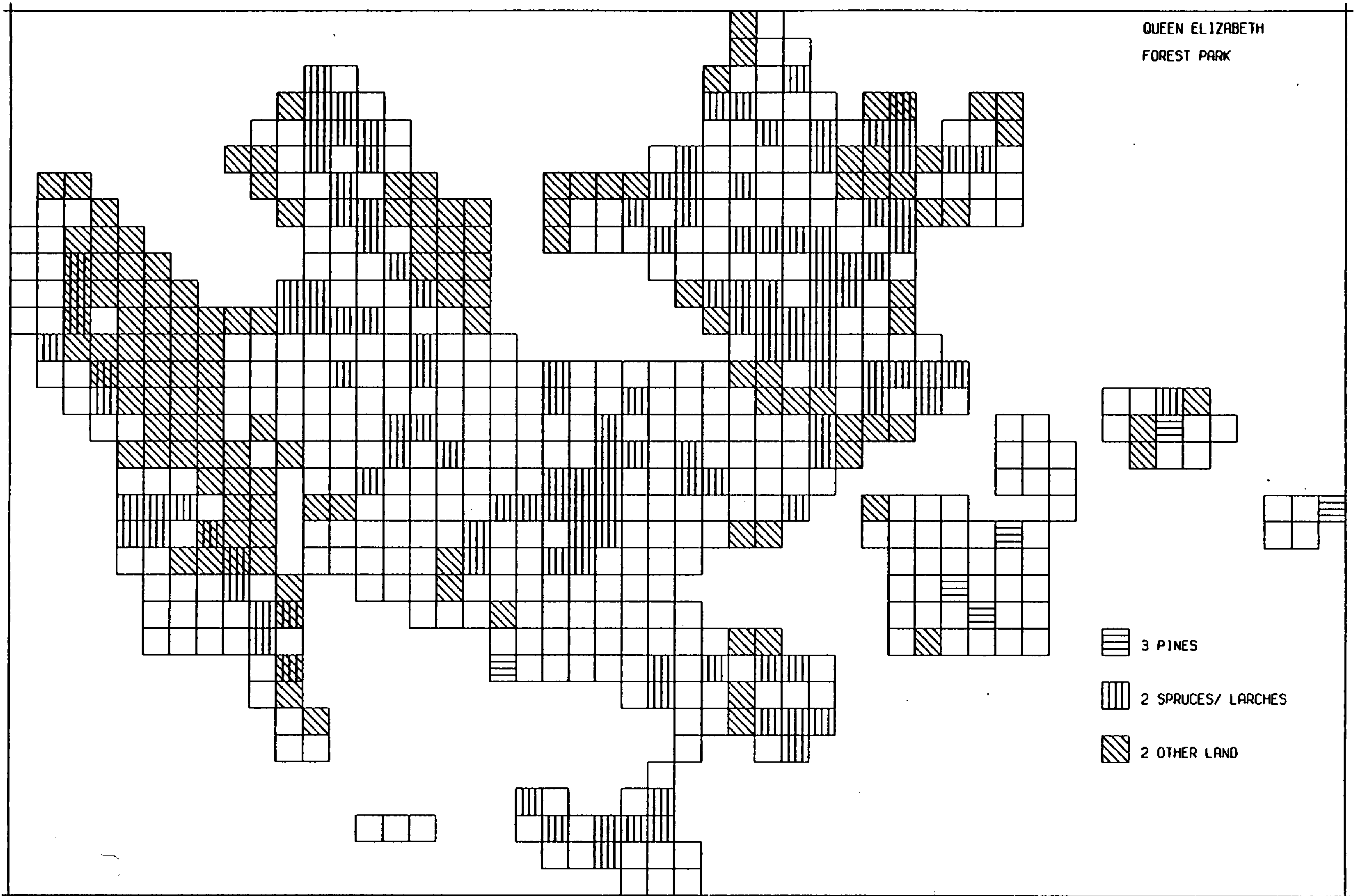


Figure 9. Tentative run of FORM_MAP for the Queen Elizabeth Forest Park.
A search for three habitat types: pines-spruces/larches-other land

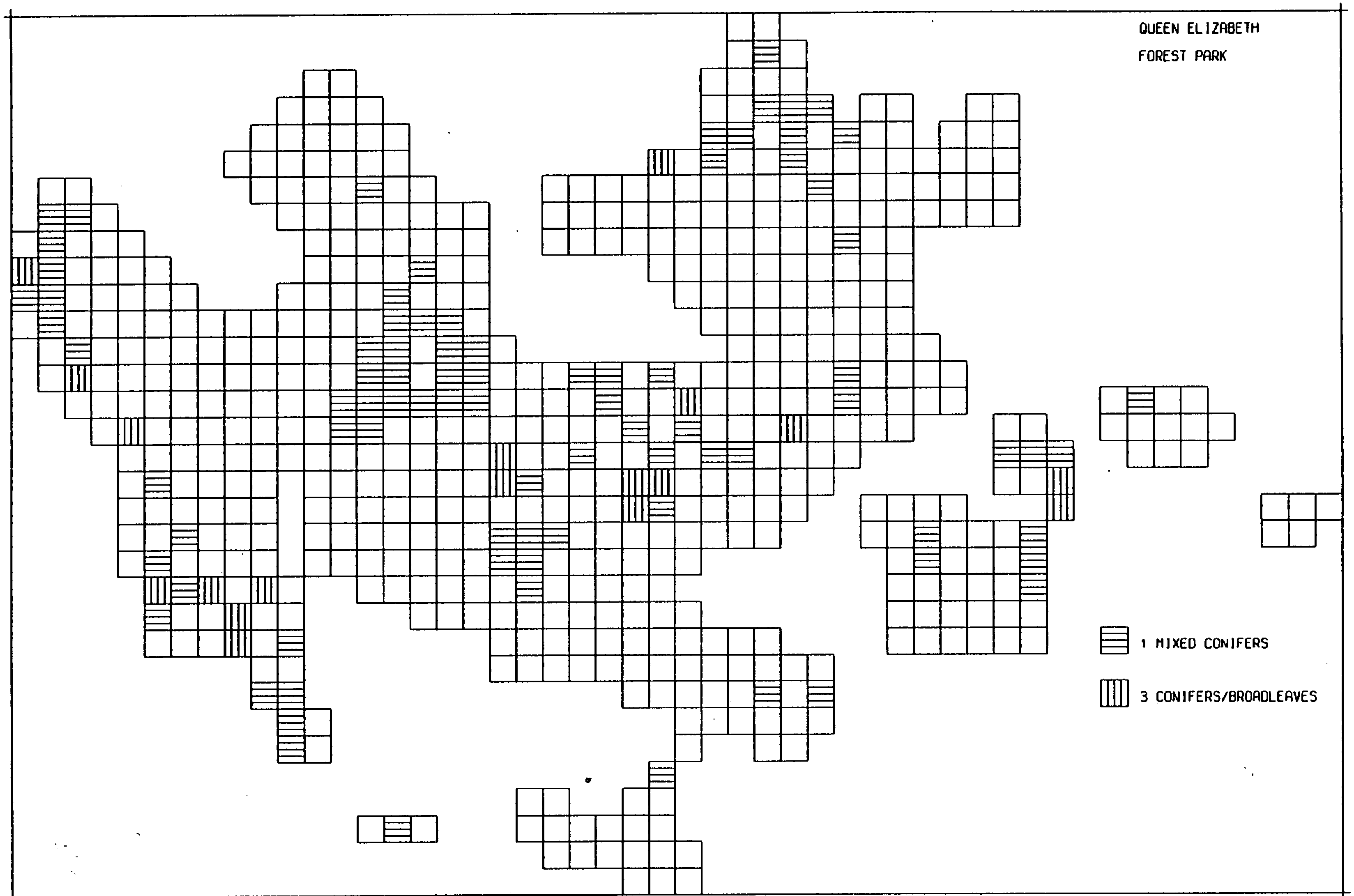


Figure 10. Tentative run of FORM_MAP for the Queen Elizabeth Forest Park.
A search for two habitat types: conifers-conifers/broadleaves

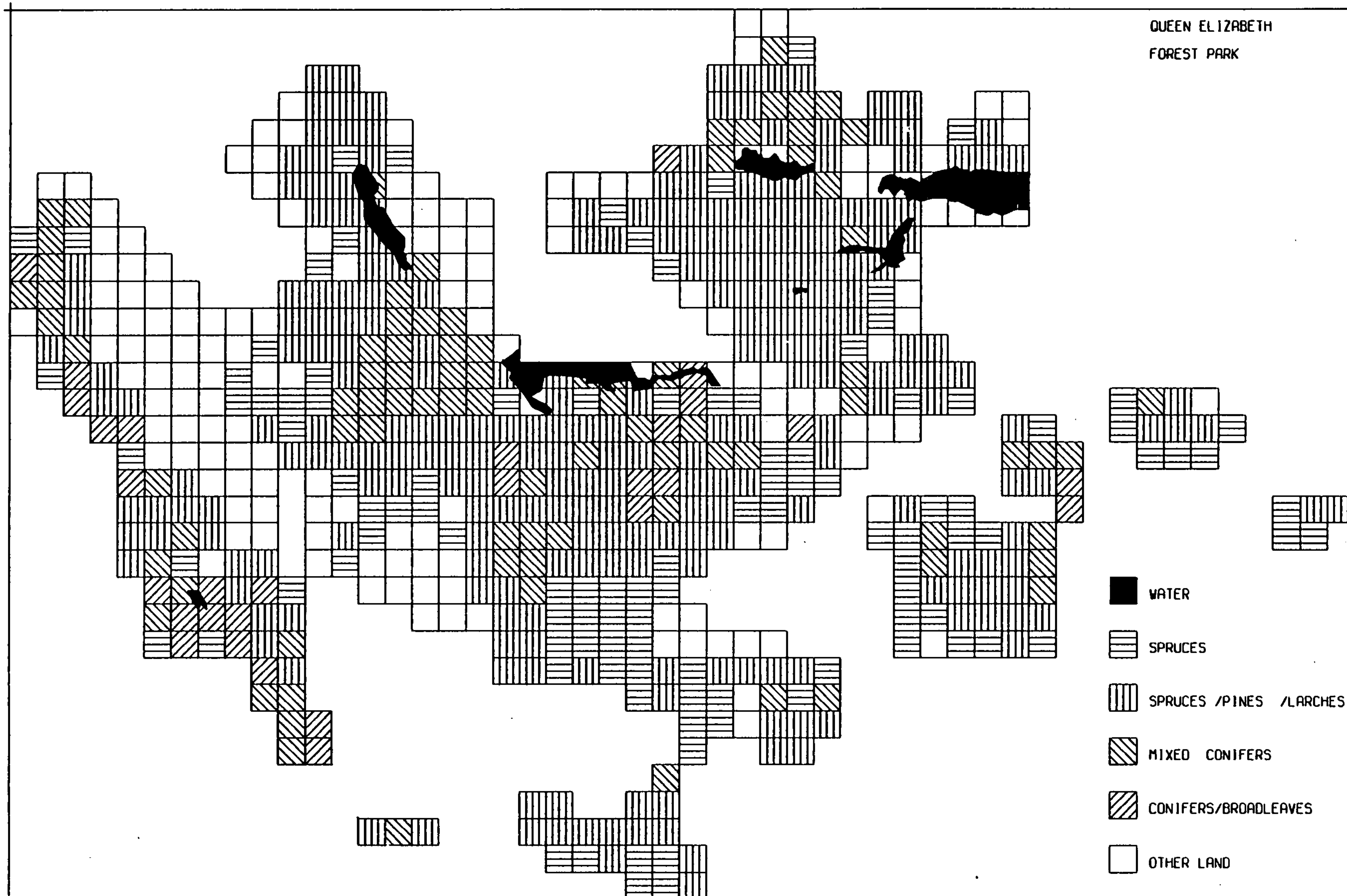


Figure 11. A map of the Queen Elizabeth Forest Park showing the spatial habitat type pattern finally selected during the data base run phase of FORM

CHAPTER SEVEN. MODEL BASE OF FORM - DESIGN PHASE

7.1 INTRODUCTION

In order for the forest manager to perform the management function of his forest, he must be able to forecast the output of alternative management strategies with respect to his management objectives through time. Forecasting is a process which requires a suitable model and response data with which to enter the model. The model may be a more or less simplified or elaborate representation of the forest system depending on availability of data, while response data are information on relationships among variables, for example, volume of timber in relation to age of trees or recreation visitor days in relation to species mixture.

Temporal based information is very important in forest management with multiple objectives, for several reasons. First, timber production is a function of time and multiple criteria decision-making would require all other forest products to be expressed in a similar fashion. Second, information about the level of various forest products available at different times during the planning horizon could facilitate planning efforts in the long-term management of forested areas. Third, the consequences of management regimes on various forest outputs occur over the life of a particular stand, since stand characteristics change according to different regimes with time, causing forest outputs to also change.

FORM-CFGENS is a model designed to simulate the output of various forest products for a number of management regimes through time. The following sections describe the structure of the model and some graphical outputs obtained when FORM_CFGENS was implemented in the Queen Elizabeth Forest Park.

The management regimes which have been included in the model are the most commonly considered in British forestry practice. These involve the two basic polar silvicultural treatments, namely, the marginal thinning regime and the non-thinning regime and 5 variations of the marginal thinning regime, the delayed thinning by 5 and 10 years and the extended rotation by 5, 10 and 15 years (see chapter 6). These regimes have been examined in association with four of the habitat types identified for the Queen Elizabeth Park, that is spruces, spruces/pines/larches, mixed conifers and conifers/broadleaves.

The other two habitat types, the overmature forest and the 'other land' type (open land, land with scattered individual trees or small blocks of trees, grassland and moorland) can not be treated by any of these regimes, because they produce no timber. The decision variables relating to these two habitat types refer to retention of their land, because they have a value for recreation, game sporting and conservation. The values produced by FORM_CFGENS are used as input values in the multi-objective model.

7.2 STRUCTURE OF THE MODEL

FORM-CFGENS produces output yields at time intervals specified by the user for a number of iterations also specified by the user. The time steps in association with the number of iterations constitute the planning horizon. That is if a time step of 5 years is used for 5 iterations, the planning horizon is equal to 25 years.

Another piece of information which has also to be inserted interactively in the model is the interest rate, which allows for time adjustment of the budgeting procedure.

The baseline year can be set equal to the current year or equal to the year for which the inventory subcompartment data file is available. For the Queen Elizabeth case study year 1986 has been used, because the corresponding subcompartment data file was made available by the Forestry Commission for this investigation.

The run process of the model is shown diagramatically in Figure 12. The forest manager must decide at the start of the run whether or not he/she wishes to do replanting at the end of each iteration. If the reply is negative he should run FORM_CFGENS_MAIN1S which does not assume replanting operations. If the reply is positive he is prompted to run FORM_CFGENS_MAIN2S which at the end of each iteration requires a file name in order to save the clear-felled subcompartments for replanting at the subsequent iteration.

Figures 13 and 14 show the structure plans of the two versions of FORM_CFGENS.

The input values in each version include:

* yield models,
* dispersed recreation models,
* water-based recreation models,
* a deer stalking model,
* price-size relationships,
* average costs per unit area of silvicultural operations, and
* the forest inventory subcompartment data file.

The output values include:

* timber yields, in m^3 per unit area per unit time
* dispersed recreation, in visitor days per unit area per unit time
* water-based recreation, in visitor days per unit area per unit time
* deer stalking, in shooting days per unit area per unit time

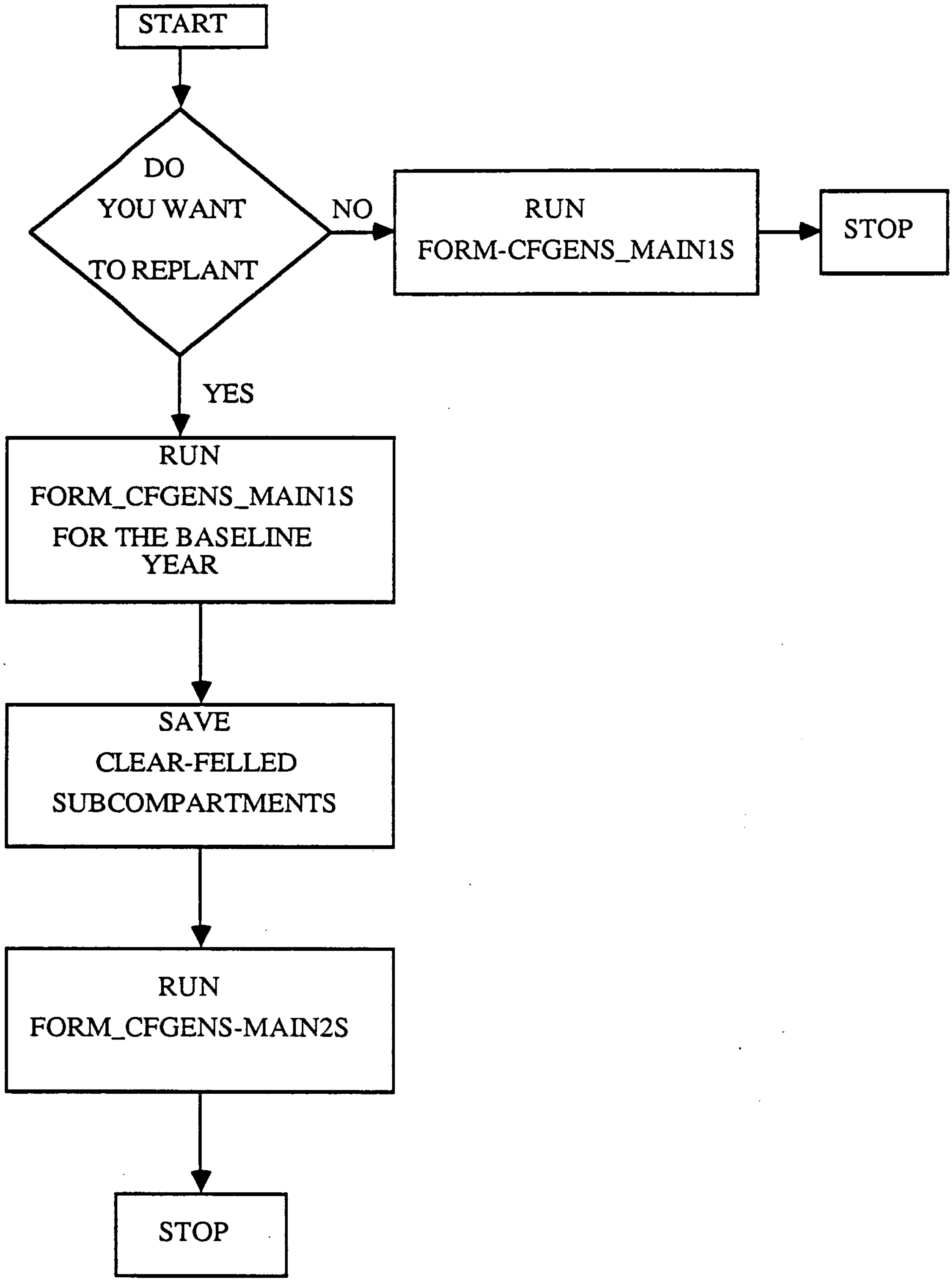


Figure 12. Run process of FORM-CFGENS

```
Specify arrays and variables
Initialize: - Iteration number equal 0
            - Baseline year equal current year
Enter:      - Time step for each run
            - Number of iterations
            - Interest rate
Increment iteration number
READ budget data file
LOOP over 6 habitat type units
    IF unit less than 4
        READ deer hunting parameters from the hunting curves data file
        LOOP over 7 management strategies
            LOOP over the 16 species groups in the regime file
                READ number of species and yield classes
                READ species list
                READ regime for each yield class
                STORE optimum felling age for each yield class
                READ standing volume parameters per tree and per stand
                READ thinning volume parameters per tree and per stand
                READ subcompartment data base parameters
                LOOP over subcompartments
                    COMPUTE number of rotations, age class (5-year interval)
                    STORE upper and lower boundaries of each age class
                    COMPUTE area of stand, cost of forestry operations
                    LOOP over years between lower and upper boundary of age class
                        COMPUTE thin. volume and cost of thin.(THIN subroutine)
                        COMPUTE fell. volume and cost of fell. (FELL subroutine)
                        COMPUTE dis. recr. and dis.recr. cost (DREC subroutine)
                        COMPUTE wat. recr. and wat. recr. cost (WREC subroutine)
                        COMPUTE deer hun. and deer hun. cost (DHUN subroutine)
                    END of loop of years between each age class
                    SUM of tim. volume, dis.recr.,wat. recr.,deer hun.,thin. and
                              fell. areas, cost of operations
                END of subcompartments loop
                SUM of tim.volume, dis.recr.,wat.recr.,deer hun.,thin.and fell. areas,cost of operations
            END of species groups loop
            COMPUTE per unit area values of tim.volume,dis.recr.,wat.recr.,cost of operations
        END of management strategies loop
    END of IF condition
    CALCULATIONS FOR UNITS 5 AND 6
    READ subcompartment data base parameters
    LOOP over subcompartments
        COMPUTE dis.recr.,wat.recr.,deer hun.,cost of operations
    END of subcompartments loop
    SUM of dis.recr.,wat.recr.,deer hun.,cost of operations.Value per unit area
    END of habitat type units loop
WRITE MODEL OUTPUT: t.volume,dis.recr.,wat.recr.,deer hun.,cost/unit area/year
END of iteration
Increment time step
IF iteration number less than specified GOTO top. Increment iteration number
END of program.
```

FIGURE 13. STRUCTURE PLAN OF FORM_CFGENS_MAIN1S

```
Specify arrays and variables
Initialize: - Iteration number equal 0
            - Baseline year equal current year
Enter:      - Time step for each run
            - Number of iterations
            - Interest rate
Increment iteration number
Enter:      - Name of clear-felled area data file
            - Unit number of transferal from, Unit number of transferal into
            - Compartment number,subcompartment number,component number
            - New species name, yield class of new species
STORE transferal areas
READ budget data file
LOOP over 6 habitat type units
    IF unit less than 4
        READ deer hunting parameters from the hunting curves data file
        LOOP over 7 management strategies
            LOOP over the 16 species groups in the regime file
                READ number of species and yield classes
                READ species list
                READ regime for each yield class
                STORE optimum felling age for each yield class
                READ standing volume parameters per tree and per stand
                READ thinning volume parameters per tree and per stand
                READ subcompartment data base parameters
                LOOP over subcompartments
                    COMPUTE number of rotations, age class (5-year interval)
                    STORE upper and lower boundaries of each age class
                    COMPUTE area of stand, cost of forestry operations
                    LOOP over years between lower and upper boundary of age class
                        COMPUTE thin. volume and cost of thin.(THIN subroutine)
                        COMPUTE fell. volume and cost of fell. (FELL subroutine)
                        STORE clear-felled stands of each unit (STORE subroutine)
                        COMPUTE dis. recr. and dis.recr. cost (DREC subroutine)
                        COMPUTE wat. recr. and wat. recr. cost (WREC subroutine)
                        COMPUTE deer hun. and deer hun. cost (DHUN subroutine)
                        END of loop of years between each age class
                    SUM of tim. vol., dis.recr.,wat. recr.,deer hun.,thin.+fell.areas,cost of operations
                    END of subcompartments loop
                SUM of tim.volume, dis.recr.,wat.recr.,deer hun.,thin.and fell. areas,cost of operations
                END of species groups loop
            COMPUTE per unit area values of tim.volume,dis.recr.,wat.recr.,cost of operations
            END of management strategies loop
        END of IF condition
    CALCULATIONS FOR UNITS 5 AND 6
    READ subcompartment data base parameters
    LOOP over subcompartments
        COMPUTE dis.recr.,wat.recr.,deer hun.,cost of operations
        END of subcompartments loop
    SUM of dis.recr.,wat.recr.,deer hun.,cost of operations,Value per unit area
    END of habitat type units loop
WRITE MODEL OUTPUT: t.volume,dis.recr.,wat.recr.,deer hun.,cost/unit area/year
END of iteration
ENTER file name to save clear-felled areas for replanting at next iteration
Increment time step
IF iteration number less than specified GOTO top. Increment iteration number
END of program.
```

FIGURE 14. STRUCTURE PLAN OF FORM_CFGENS_MAIN2S

* budget values, in sterling(£) per unit area per unit time

Output values are estimated for each regime and each habitat type and can be generated in two different formats, tabular and graphic. The graphics are produced with the EASYGRAPH software which runs on the EMAS mainframe computer (IBM 370-XA). The model is written in FORTRAN77 and runs also on EMAS.

The basic structure of both models involves three main loops at each iteration. The first loop is over the habitat types , the second over the management regimes and the third over the species groups. The names of species were coded and used in the same format for each management regime.

Within each species group the program scans the subcompartment data base in order to identify those subcompartments which include the corresponding species. For each such subcompartment (stand) then the age class and the number of rotation periods the stand should have passed through if clear-felling had taken place at the optimum felling age and replanting with the same species followed the next year, are calculated.

Other calculations are done at this stage through calling a number of subroutines. In the no-replanting version five subroutines have been incorporated: 1) FELL subroutine, which computes the felling volume 2) THIN subroutine, which computes the thinning volume 3) DREC subroutine, which estimates the forest dispersed recreation visitor days 4) WREC subroutine, which estimates the forest water-based recreation visitor days and 5) DHUN subroutine, which estimates the deer shooting days. Each of these subroutines calculates also the expenditure and revenue associated with this specific subcompartment.

The replanting version, in addition to these subroutines, also includes the STORE subroutine, which stores the clear-felled subcompartments for replanting.

At the end of each loop the output values of each item are aggregated . The final values are average estimates per unit area and unit time.

The THIN subroutine computes the thinning volume using the thinning volume polynomial equations (presented in chapter 3), which have been derived statistically from the yield models. The FELL subroutine computes the felling volume using both thinning and standing volume polynomial equations (chapter 3), since the felling volume can be obtained by adding the standing volume and the thinning volume at the specific age of felling.

The DREC and WREC subroutines use the corresponding statistical models presented in chapter 3, which are tailored for the structure of FORM_CFGENS.

In the DHUN subroutine the cull of juveniles for the Queen Elizabeth case study in 1986(baseline year) was taken as 35 percent and the population of red deer as one of high performance and low mortality. The information was provided by the Aberfoyle Forest District staff (personal communication). Roe deer stalking has not been included in FORM at this stage of its development due to insufficient data information about roe deer population. The final tables after implementing the algorithm described in chapter 3, containing as variables age of trees and shooting days were processed through CURVEFIT software and polynomial equations of degree eight were derived in order to deal with continuous time points over the planning horizon.

The calculations for overmature growth and other land habitats (units 5 and 6) are made in a separate loop, but within the habitat type loop. This structural differentiation was necessary, because these two habitats are not productive from the timber point of view and, therefore, are not subject to the same silvicultural treatments.

The replanting version of the model includes more interactive elements than the no-replanting one. The forest manager is requested to provide the following information:

* identification number of the habitat type land has to be transferred from,
* identification number of the habitat type land has to be transferred to,
* compartment number,
* subcompartment number,
* component number,
* name of new species (coded format, but a HELP list can be invoked)
* yield class of new species

It is believed that this type of information can be rather easily provided by the forest manager, who usually has a good experience of his forest area.

Example runs of theFORM_CFGENS_MAIN1S and FORM_CFGENS-MAIN2S models are shown in Appendices 2 and 3 respectively.

7.3 THE QUEEN ELIZABETH FOREST PARK APPLICATION

The no-replanting version of the FORM_CFGENS model was run for the Queen Elizabeth Forest Park and the graphic results are displayed on pages 128 to 144. The values in tabular format are shown in Appendix 4. A planning horizon of 25 years was considered at 5-year intervals starting in 1986. Direct comparisons between the different habitat types are not possible because the areas occupied by these habitat types vary. A weighting procedure, which would allow for such comparisons is not included at this developement stage of FORM_CFGENS. This is mainly because the objective for designing this model was to produce input values for the multi-objective and multi-period optimization model.

Figures 15 to 18 show timber yields per ha and year under the seven simulated management regimes for the four habitat types, that is the spruces unit, the spruces/pines/larches unit and the conifers/broadleaves unit. The non-thinning regime shows larger outputs than the other regimes in all four habitats for the 25-year planning period. This probably happens because more trees may reach the non-thinning optimum felling age during this period, therefore increasing the volume which would be extracted if this regime would have been practised.

Figures 19 to 22 show the dispersed recreation output in visitor days per ha and year. The non-thinning regime does not appear in the graphs, because recreation visitors can not usually have access to non-thinned stands. Therefore, the forest dispersed recreation output under the non-thinning regime was assumed zero. Trees of age less than 10 years old in all fully stocked forest habitats were also assumed of zero dispersed recreation value. This was rather necessary, because the forest dispersed recreation models on which the recreation forecast process was based, were derived statistically from samples which included only trees aged between 10 and 60 years.

An increase in dispersed recreation output is expected from year 1996 to 2011, mainly under the extended rotation regimes in the spruces habitat. The same response is also observed in the spruces/pines/larches habitat until year 2006, but followed by a decrease from year 2006 to year 2011. The output of the mixed conifers habitat appears more fluctuating with peaks at different time points under the six management regimes, while the output of conifers/broadleaves habitat is expected to increase after year 2006.

For forest water-based recreation (figures 23 to 25), the impact of the non-thinning regime in all fully stocked habitats and young stands of age less than 10 years was to impose zero water-based recreation value. The reasons are the same mentioned for forest dispersed recreation output. Also the conifers/broadleaves habitat for this type of recreation does not appear in the graphs. This is because no samples with conifers/broadleaves near water-areas in the forest were available from the survey carried out in the Queen Elizabeth forest in summer 1986. Therefore no statistical models for this habitat type were obtained. The extended rotation regimes in all three habitats show much higher outputs of forest water-based recreation than the other regimes. This complies with before run expectations.

Figures 26 to 29 display deer shooting days per ha and year. No significant differences in deer stalking between the different regimes in all four fully stocked habitats should be expected according to this forecast. This may be attributed to the following reason. The average density of red deer in the forest was set equal to an optimal value, so that damage on plantantions could be minimized (Cooper and Mutch, 1979). This may not have been true in 1986 for the Queen Elizabeth Forest Park.

However, the assumption was necessary in the multi-objective optimization context, since the general utility (mathematically unknown) in the algorithm is assumed to be monotonically increasing. This means that more is preferred to less, which is generally compatible with most forest outputs, but certainly not with deer population.

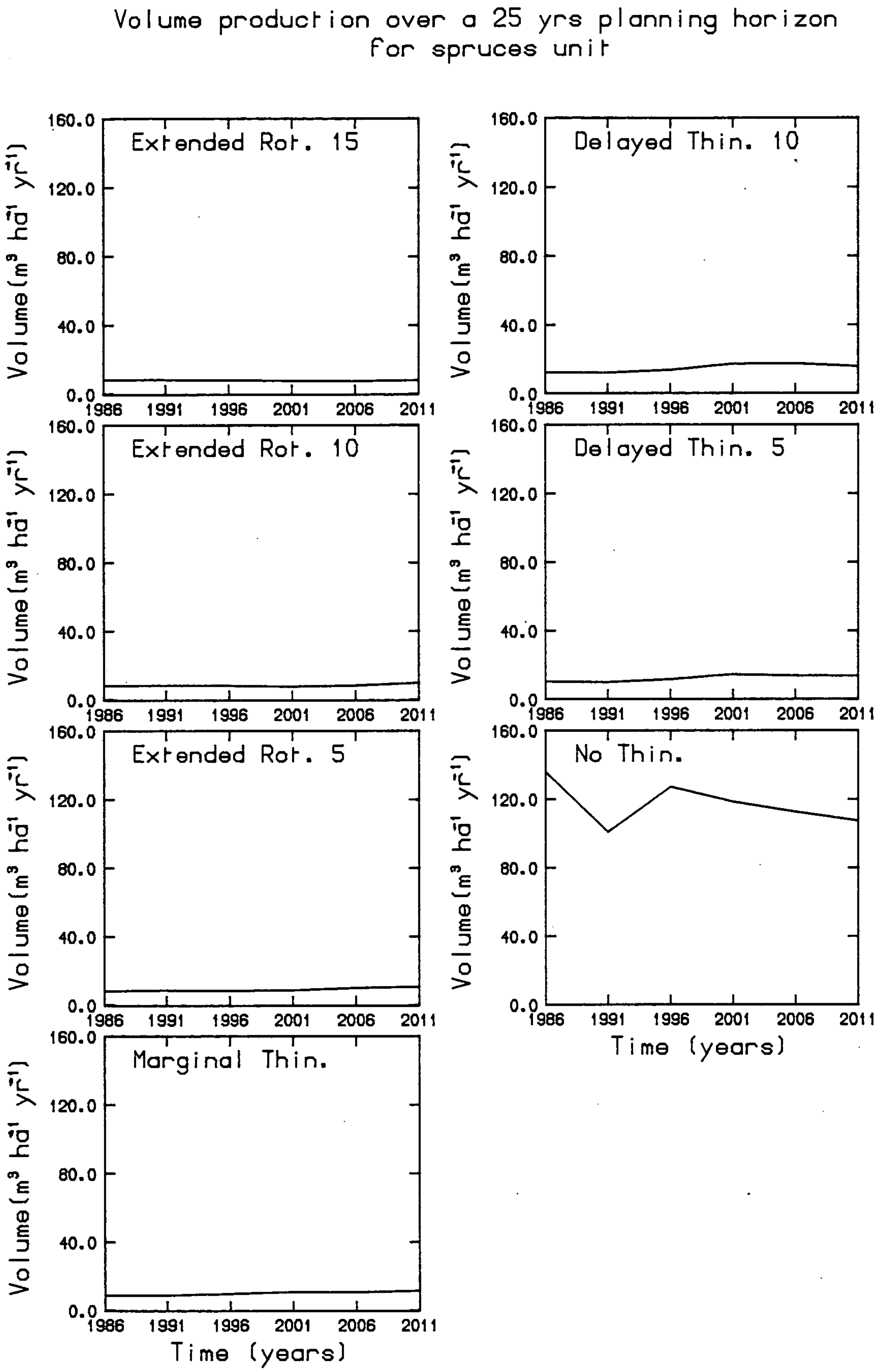
Figures 30 and 31 display dispersed recreation, water-based recreation and deer stalking for the overmature growth and other land habitats respectively. The straight horizontal lines indicate a constant output with respect to each output, over the entire planning period. This is the result of the run of the no-replanting version of the model.

The decision variables associated with overmature growth and other land habitat types refer only to the decision of retaining such areas or converting them to another habitat. In the recreation models, the transport variable which could generate fluctuations in the corresponding outputs was calculated as the average of two equations. The first equation was related to 90 percent of the forest visitors, who were assumed to come to the forest with motor transport.The second was related to the remaining 10 percent of the visitors who were assumed to come to the forest on foot. The figures were based on the results of the recreation survey carried out in the Queen Elizabeth Forest Park during the summer of 1986. The proportion of visitors was assumed to hold true throughout the planning horizon.

7.4 DISCUSSION

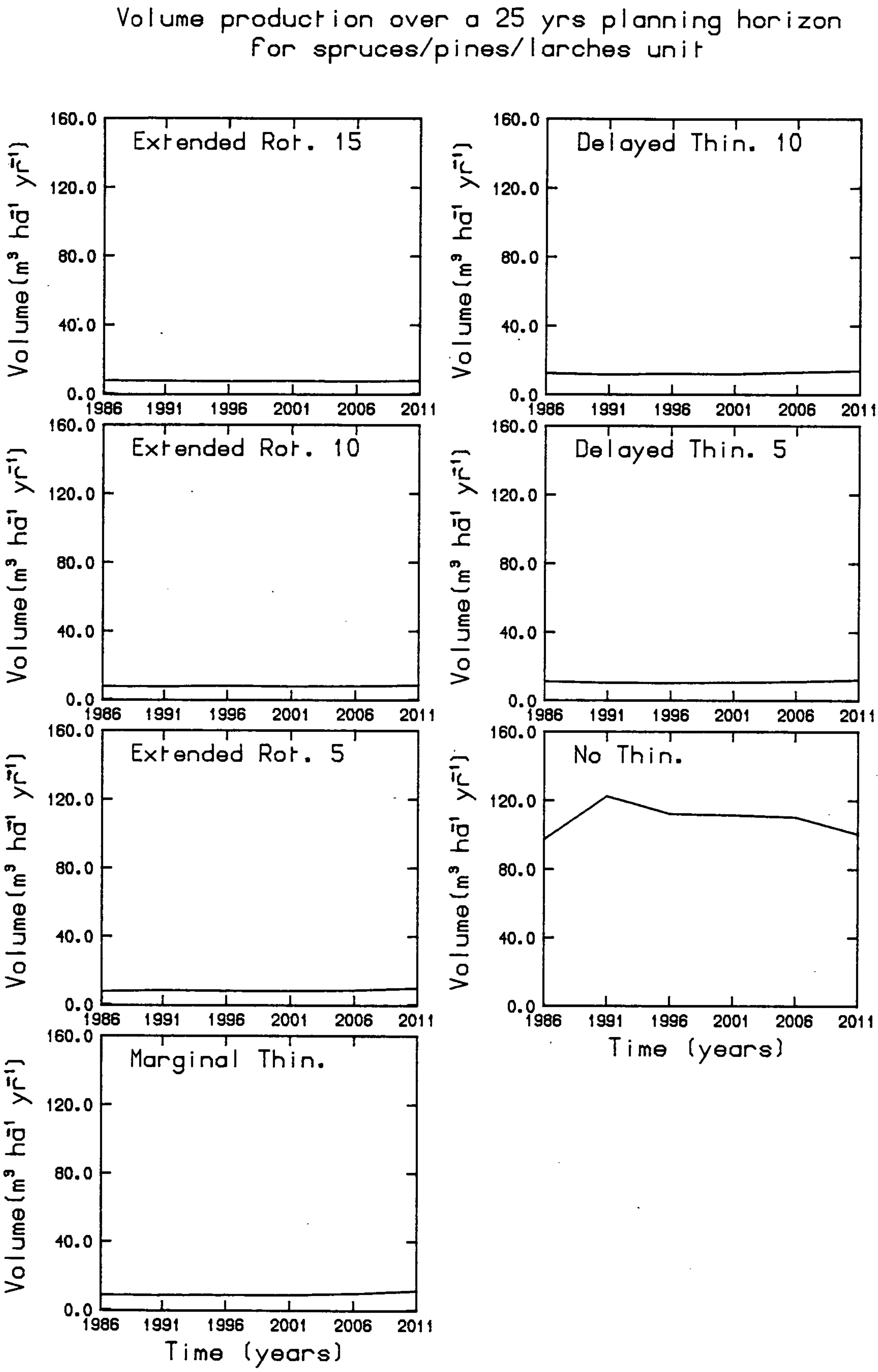
Only the no-replanting version of FORM_CFGENS was run to produce input values for the 'choice' part of FORM. This is due to time limitations regarding completion of this project. The replanting version of the model requires more input information from the forest manager for the model outputs to be reliable and that was not attempted at this development stage of FORM.

The structure of the model offers a convenient way of manipulating the subcompartment data base in association with various forest response models (see chapter 3) simultaneously to forecast outputs of many forest products over any specified planning period. Therefore, it lends itself to generalization. Caution, however, is required when attempting to generalize the response relationships, which are based on data collected from the Queen Elizabeth Forest Park. The model can also be used to generate input values in a suitable format for multi-objective optimization models.



Volume production over a 25 yrs planning horizon for spruces unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
No Thin.
Marginal Thin.
Volume(m3 ha-1 yr-1)
0.0
40.0
80.0
120.0
160.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 15



Volume production over a 25 yrs planning horizon
for spruces/pines/larches unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
No Thin.
Marginal Thin.
Volume(m³ ha⁻¹ yr⁻¹)
160.0
120.0
80.0
40.0
0.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 16

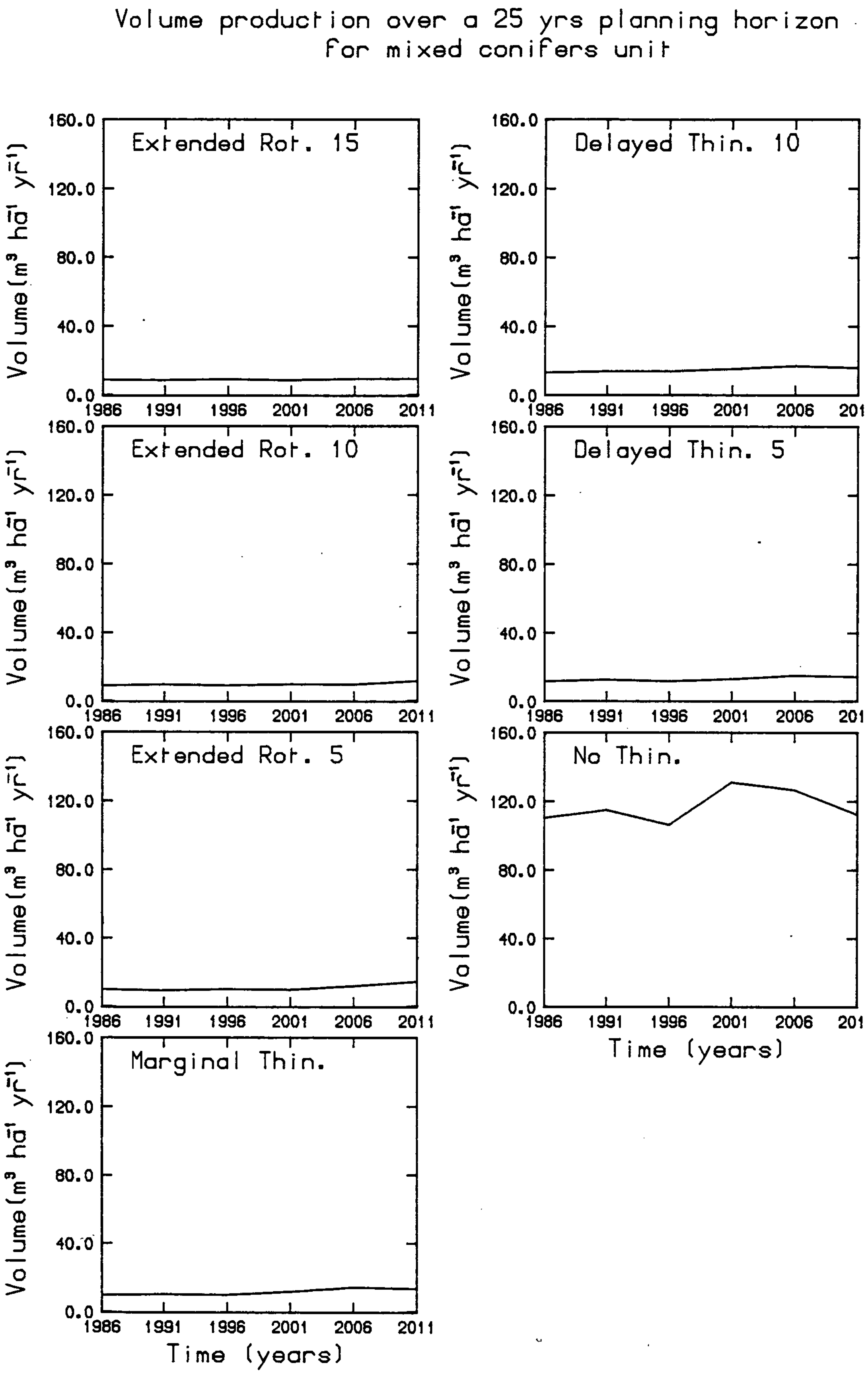

Volume production over a 25 yrs planning horizon
for mixed conifers unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
No Thin.
Marginal Thin.
Volume(m³ ha⁻¹ yr⁻¹)
160.0
120.0
80.0
40.0
0.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 17

Volume production over a 25 yrs planning horizon
for conifers/broadleaves unit

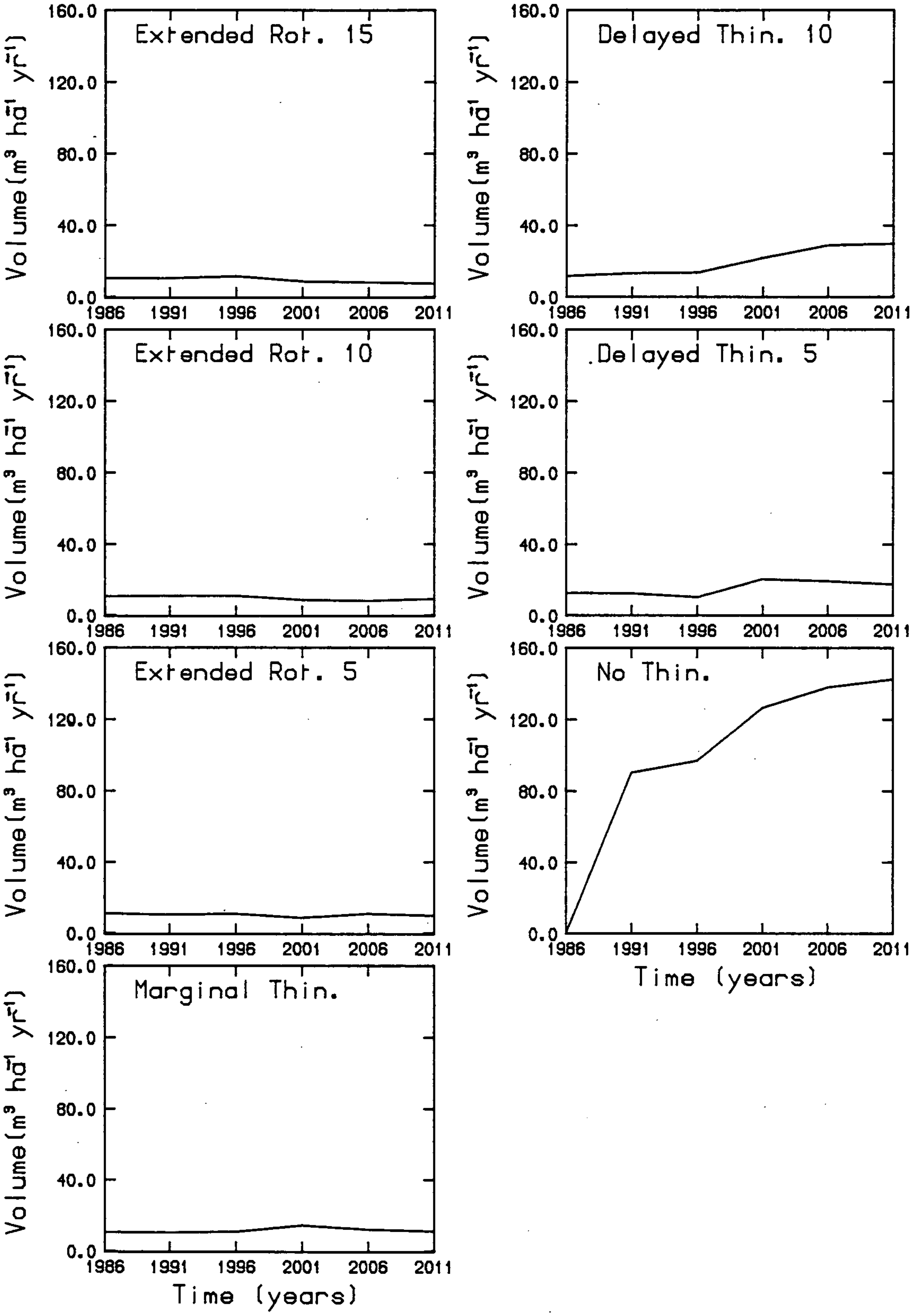
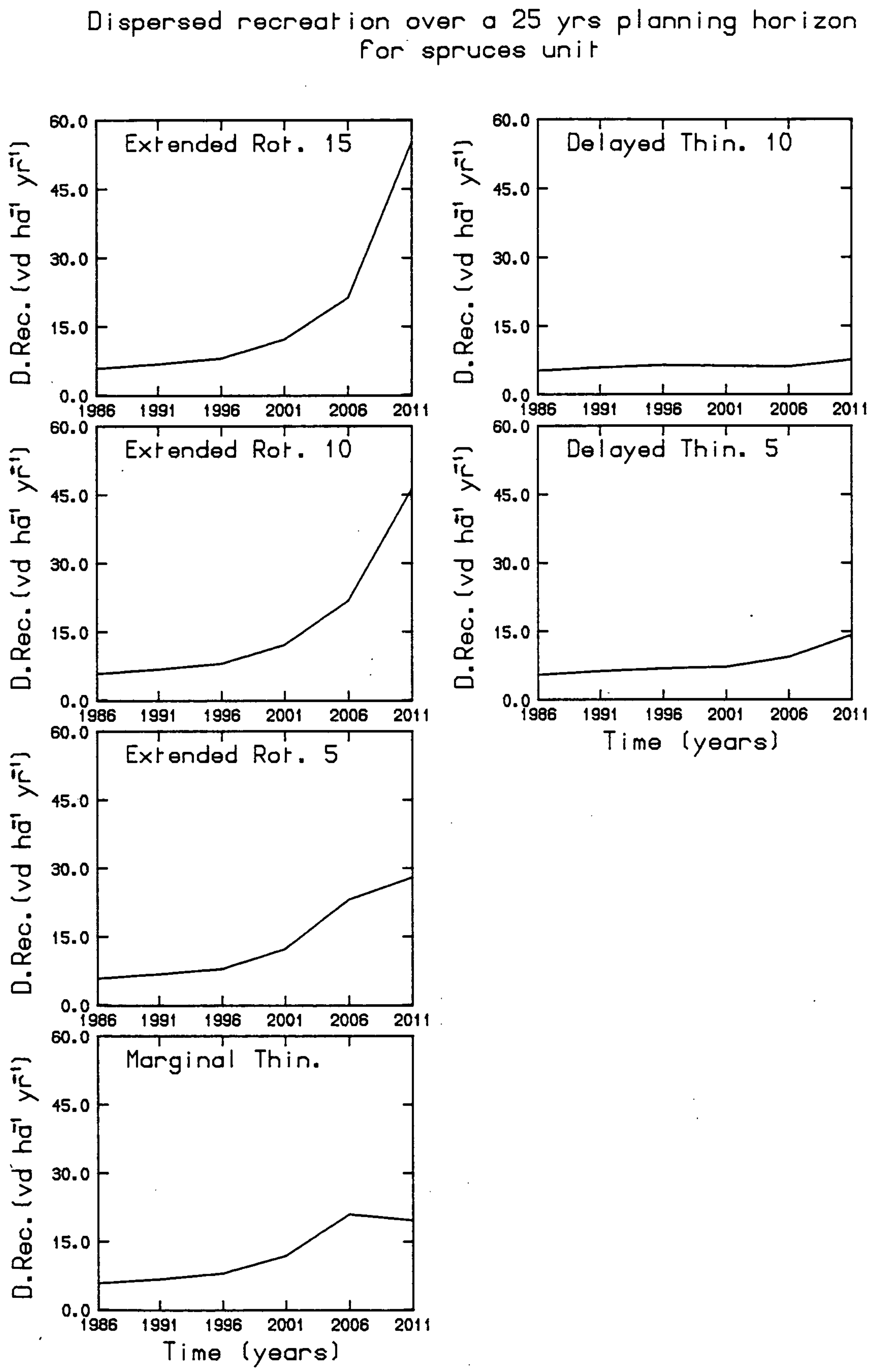
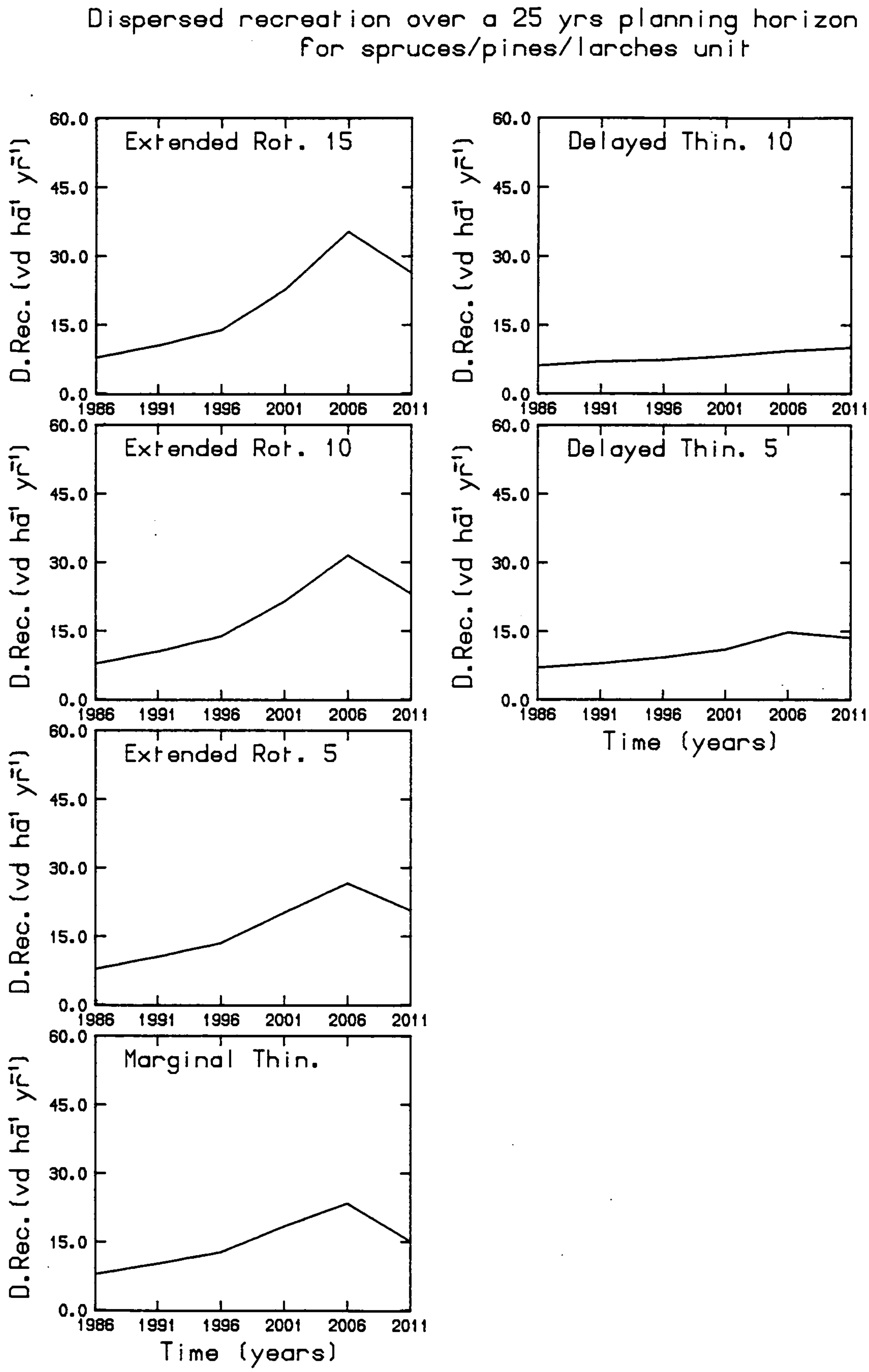


Figure 18



Dispersed recreation over a 25 yrs planning horizon for spruces unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
Marginal Thin.
D.Rec. (vd ha⁻¹ yr⁻¹)
0.0
15.0
30.0
45.0
60.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 19



Dispersed recreation over a 25 yrs planning horizon
for spruces/pines/larches unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
Marginal Thin.
D.Rec. (vd ha⁻¹ yr⁻¹)
Time (years)

Figure 20

Dispersed recreation over a 25 yrs planning horizon for mixed conifers unit

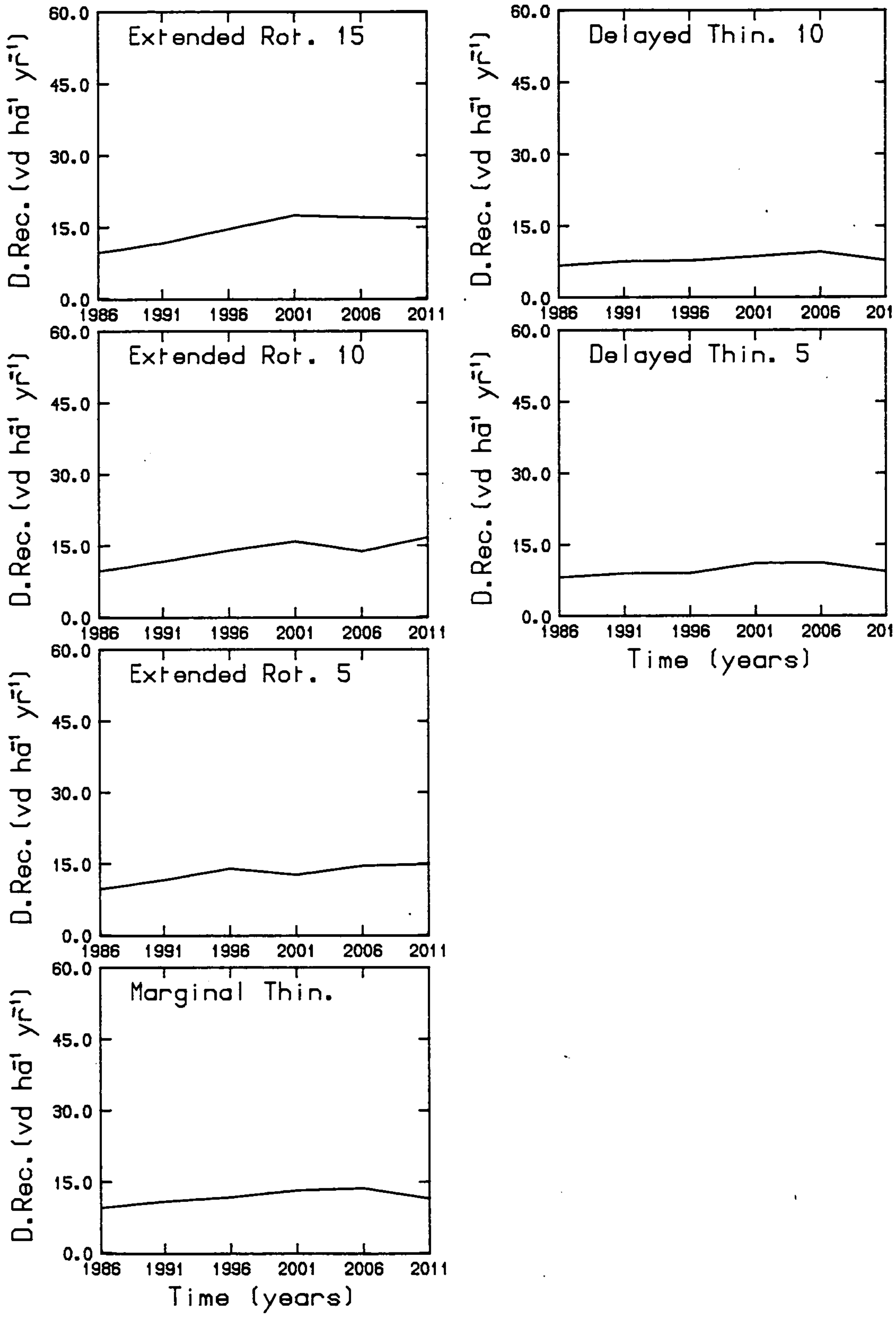


Figure 21

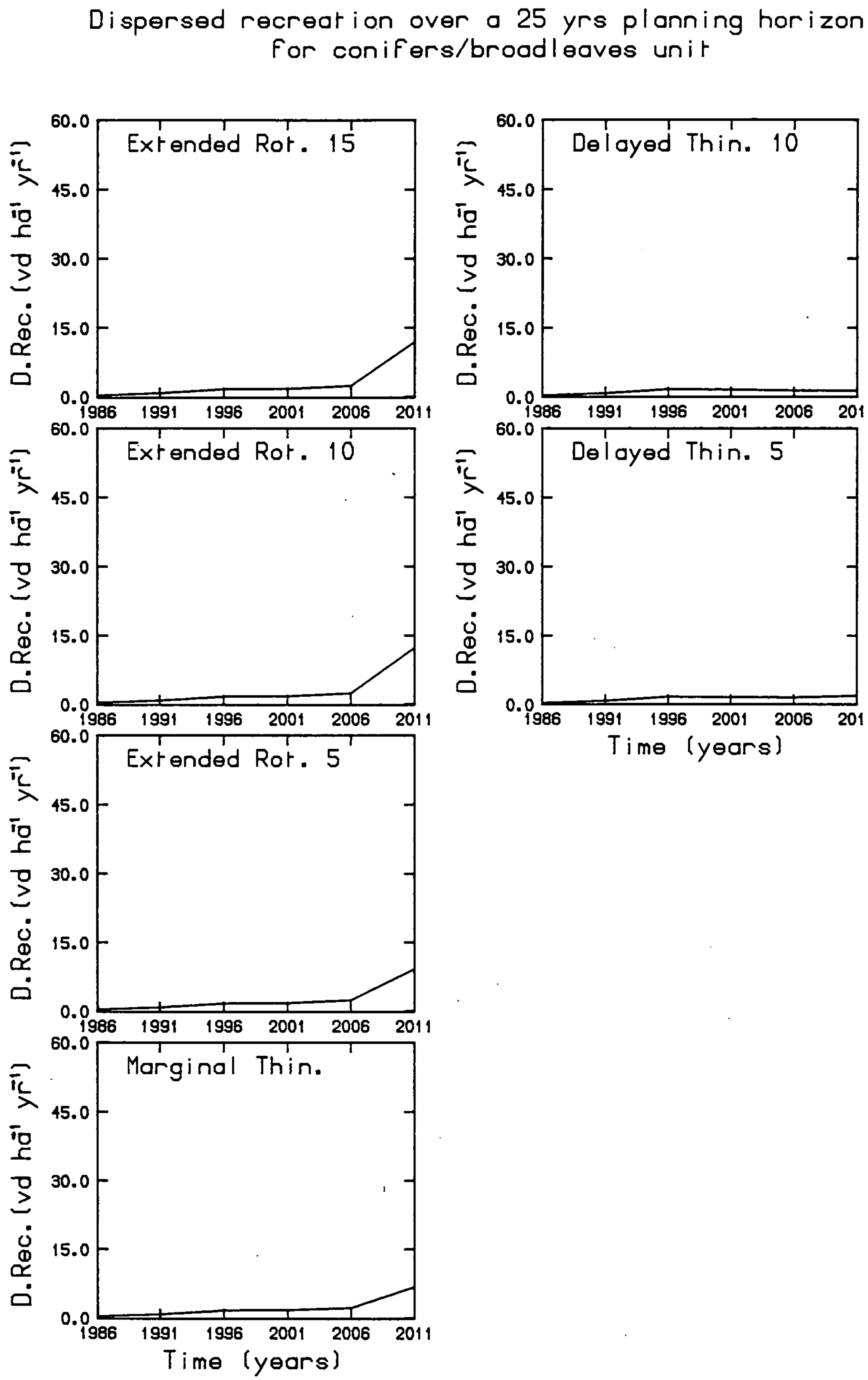

Dispersed recreation over a 25 yrs planning horizon
for conifers/broadleaves unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
Marginal Thin.
D.Rec. (vd ha⁻¹ yr⁻¹)
60.0
45.0
30.0
15.0
0.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 22

Water-based recreation over a 25 yrs planning horizon
for spruces unit

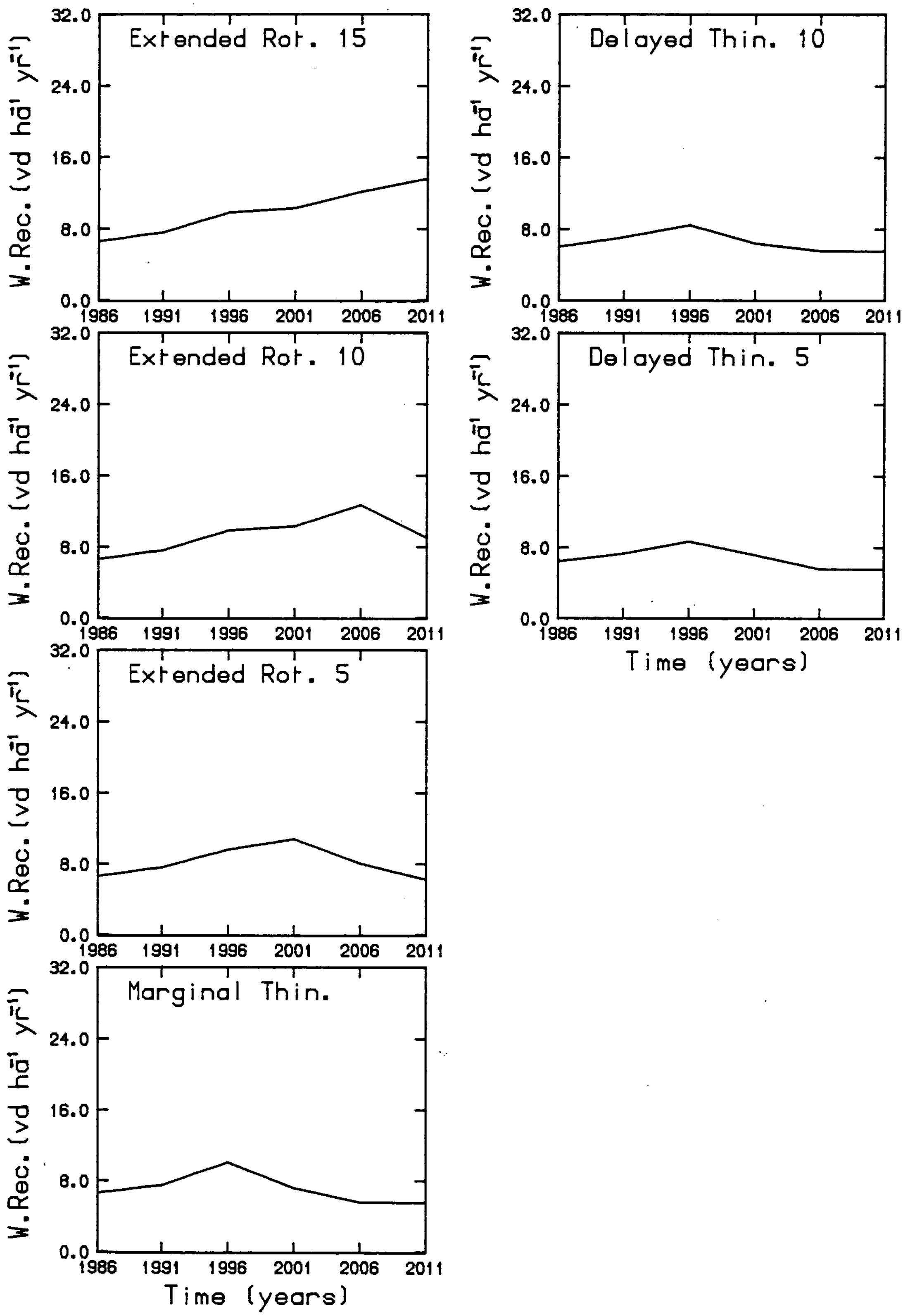


Figure 23

Water-based recreation over a 25 yrs planning horizon
for spruces/pines/larches unit

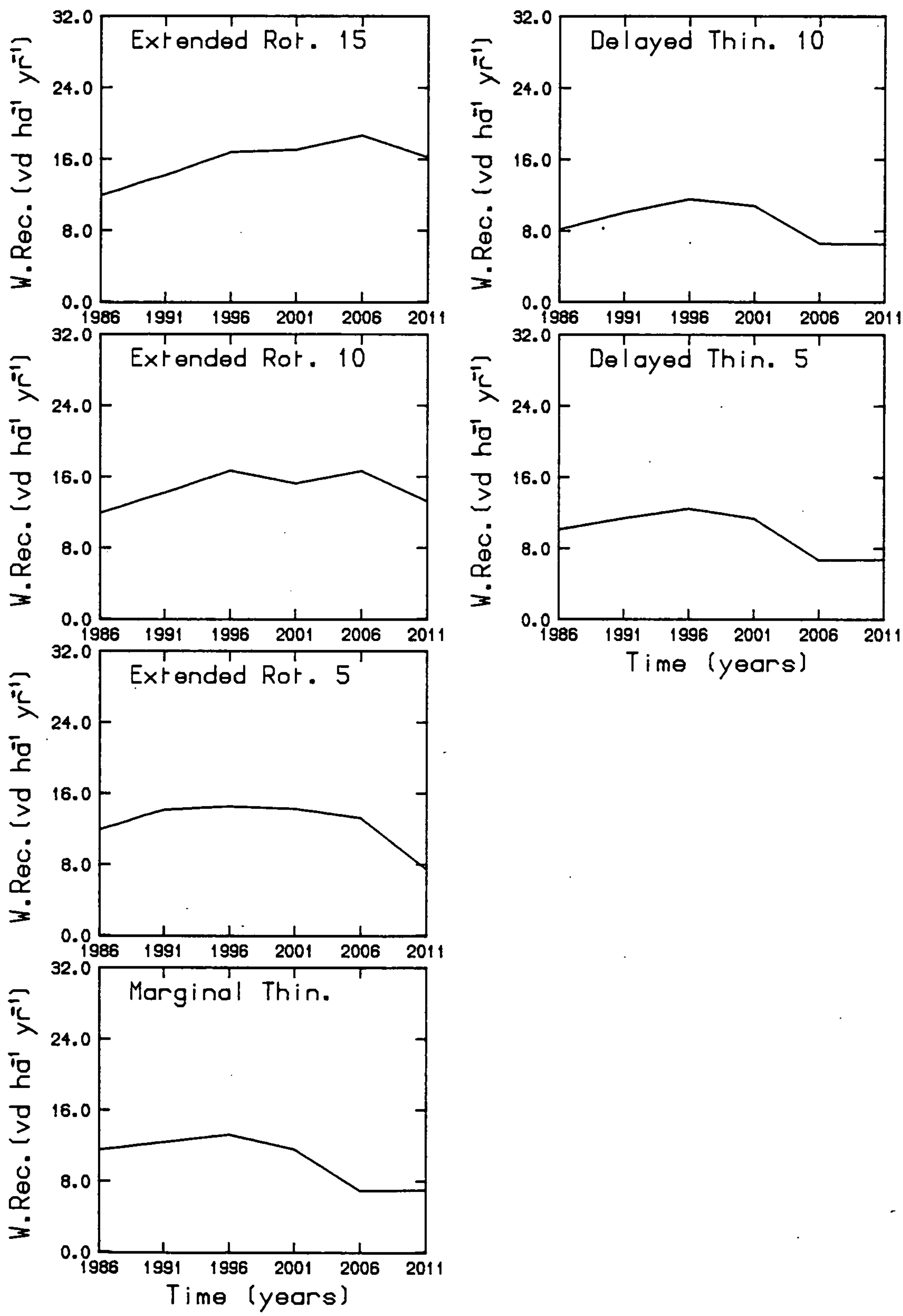


Figure 24

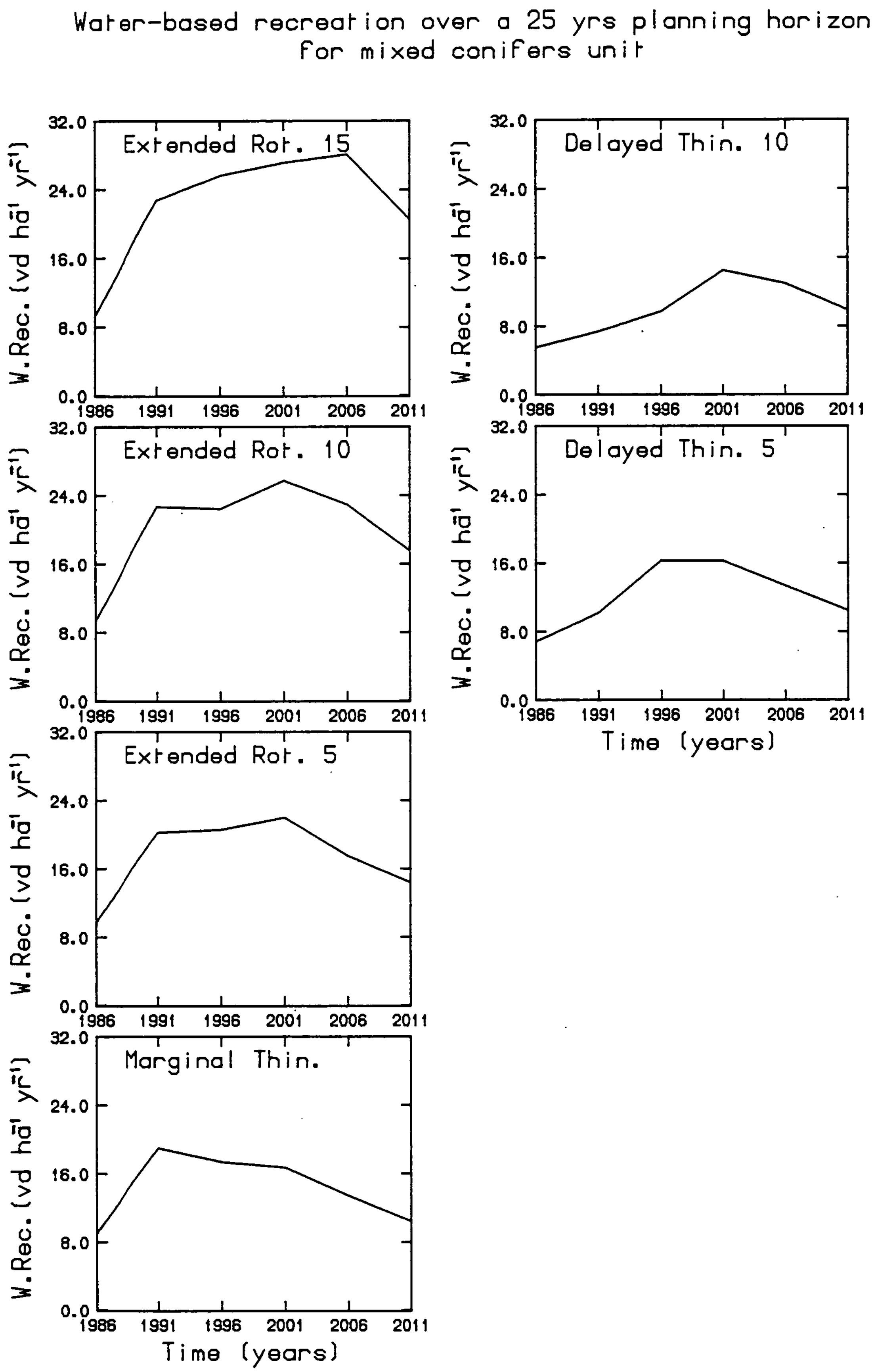

Water-based recreation over a 25 yrs planning horizon
for mixed conifers unit
Extended Rot. 15
Extended Rot. 10
Extended Rot. 5
Marginal Thin.
Delayed Thin. 10
Delayed Thin. 5
W.Rec. (vd ha⁻¹ yr⁻¹)
0.0
8.0
16.0
24.0
32.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 25

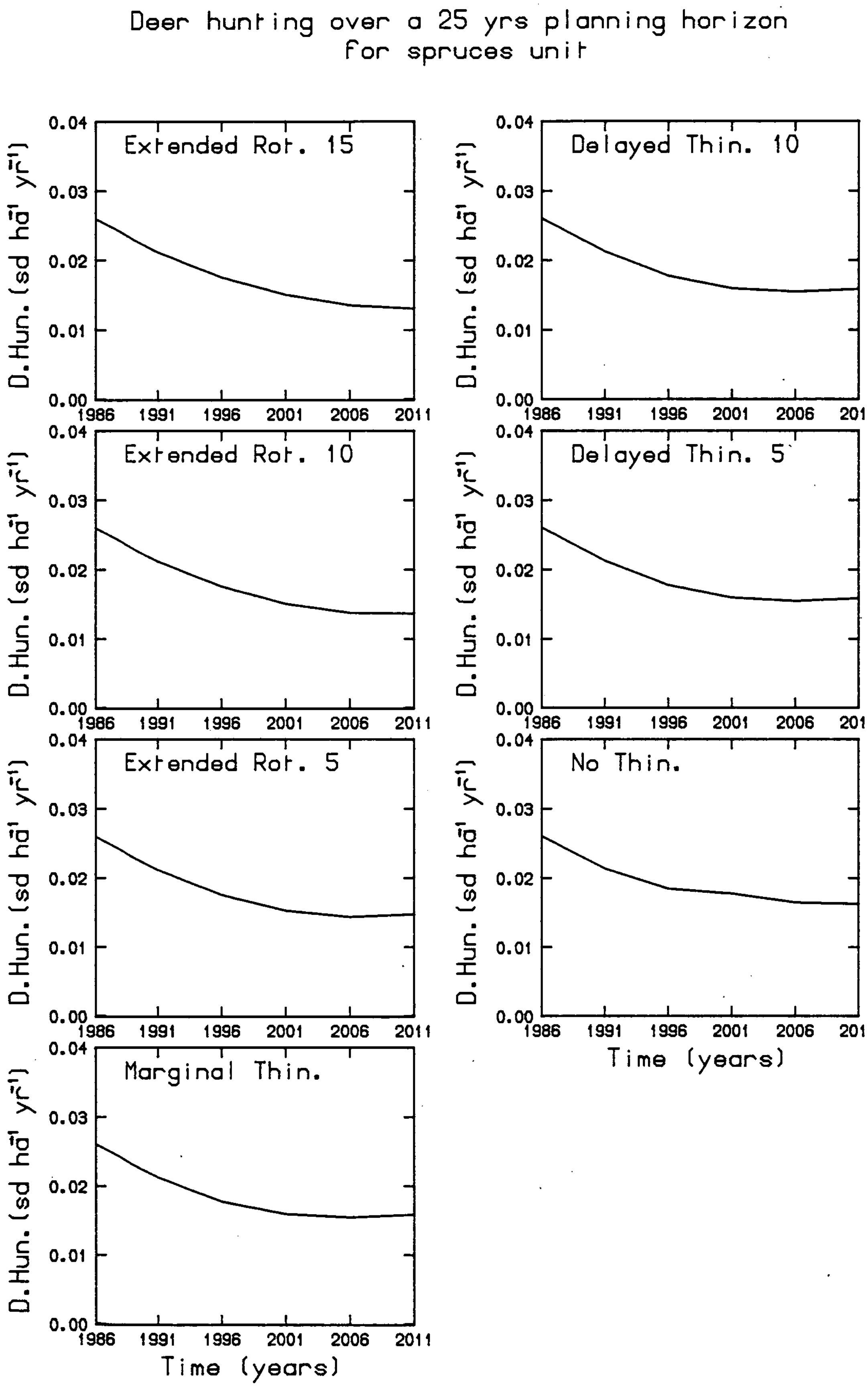
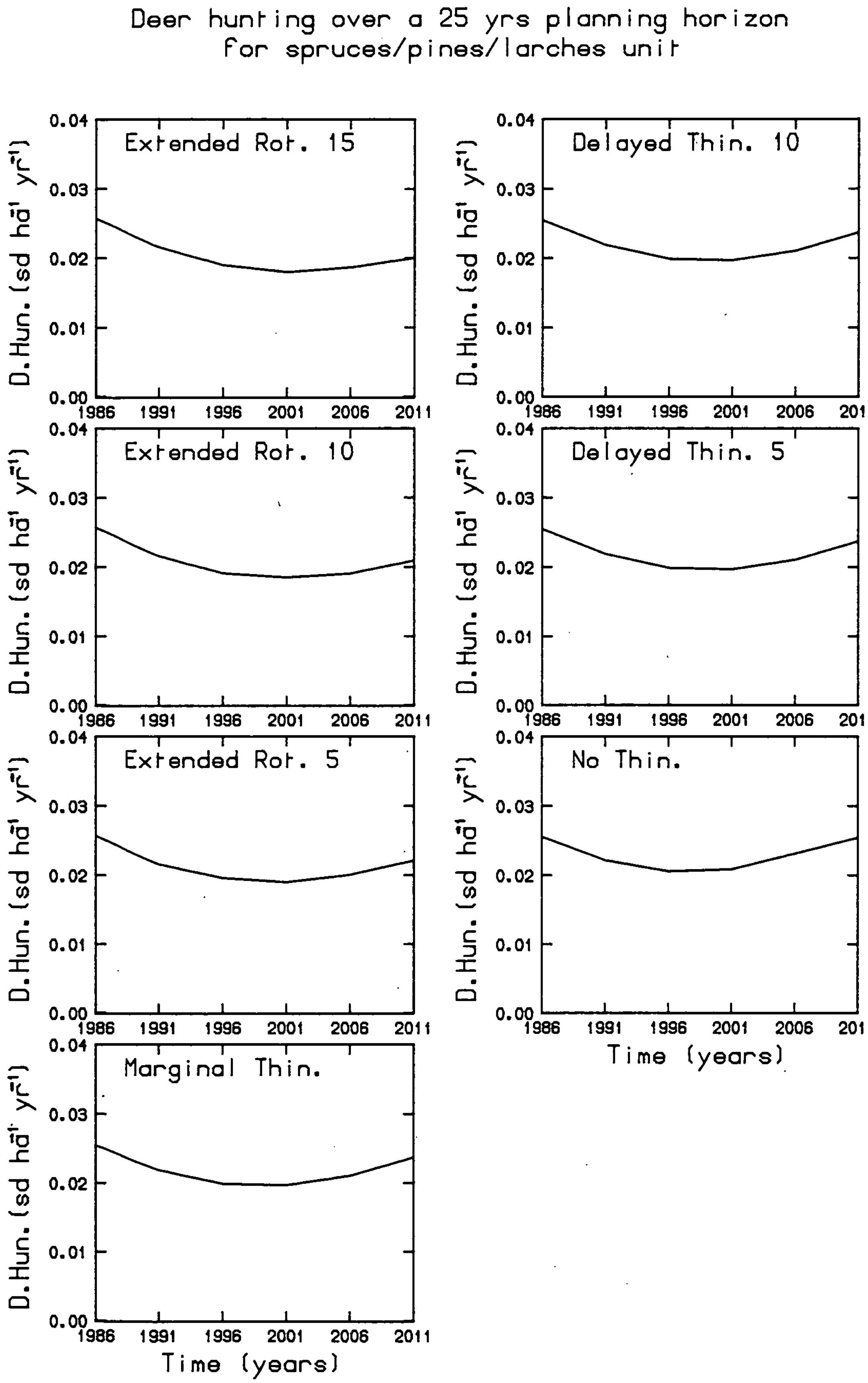
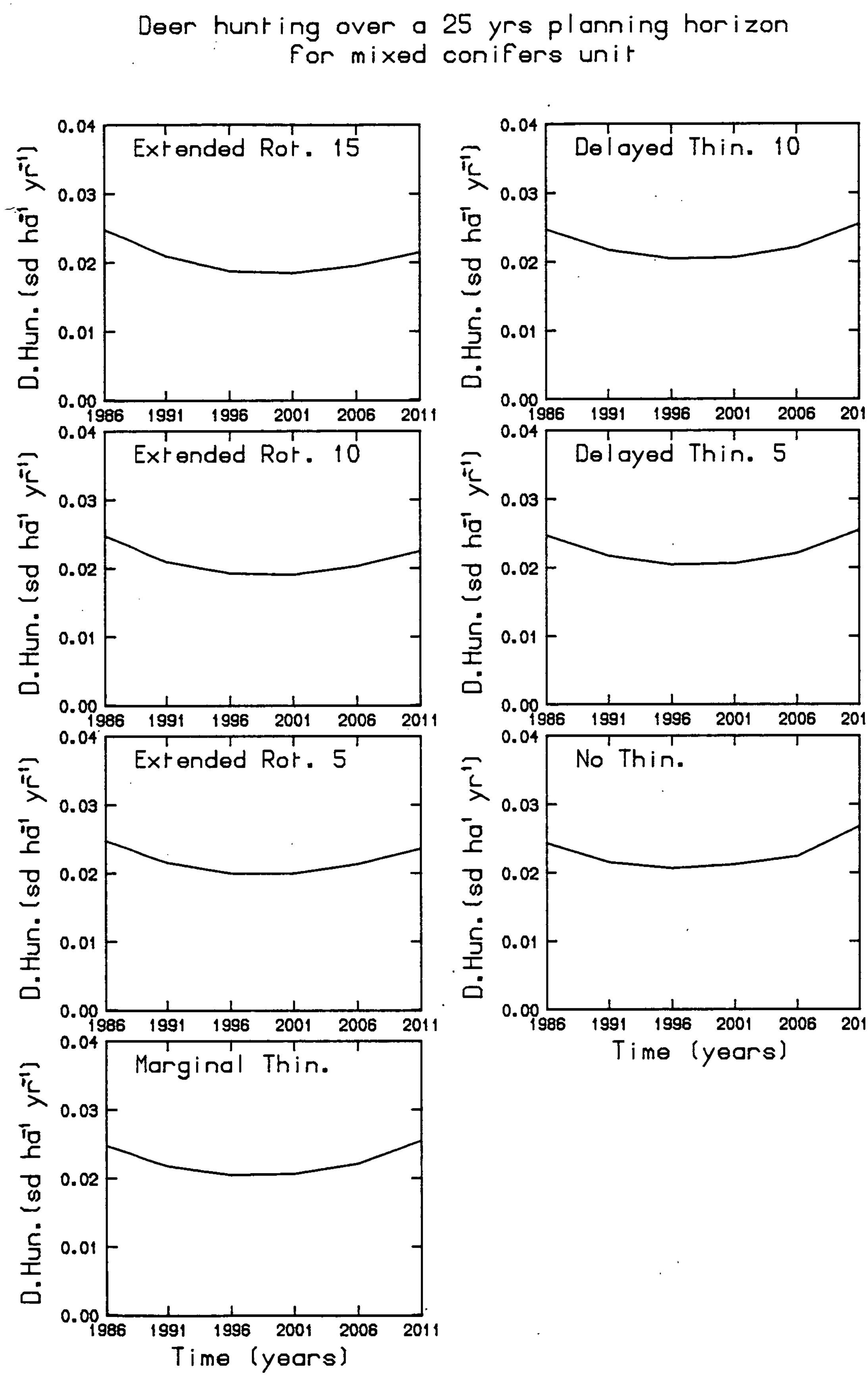

Deer hunting over a 25 yrs planning horizon
for spruces unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
No Thin.
Marginal Thin.
D.Hun. (sd ha⁻¹ yr⁻¹)
0.00
0.01
0.02
0.03
0.04
1986
1991
1996
2001
2006
2011
Time (years)

Figure 26



Deer hunting over a 25 yrs planning horizon
for spruces/pines/larches unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
No Thin.
Marginal Thin.
D.Hun. (sd ha⁻¹ yr⁻¹)
0.00
0.01
0.02
0.03
0.04
1986
1991
1996
2001
2006
2011
Time (years)

Figure 27



Deer hunting over a 25 yrs planning horizon
for mixed conifers unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
No Thin.
Marginal Thin.
D.Hun. (sd ha^{-1} yr^{-1})
0.00
0.01
0.02
0.03
0.04
1986
1991
1996
2001
2006
2011
Time (years)

Figure 28

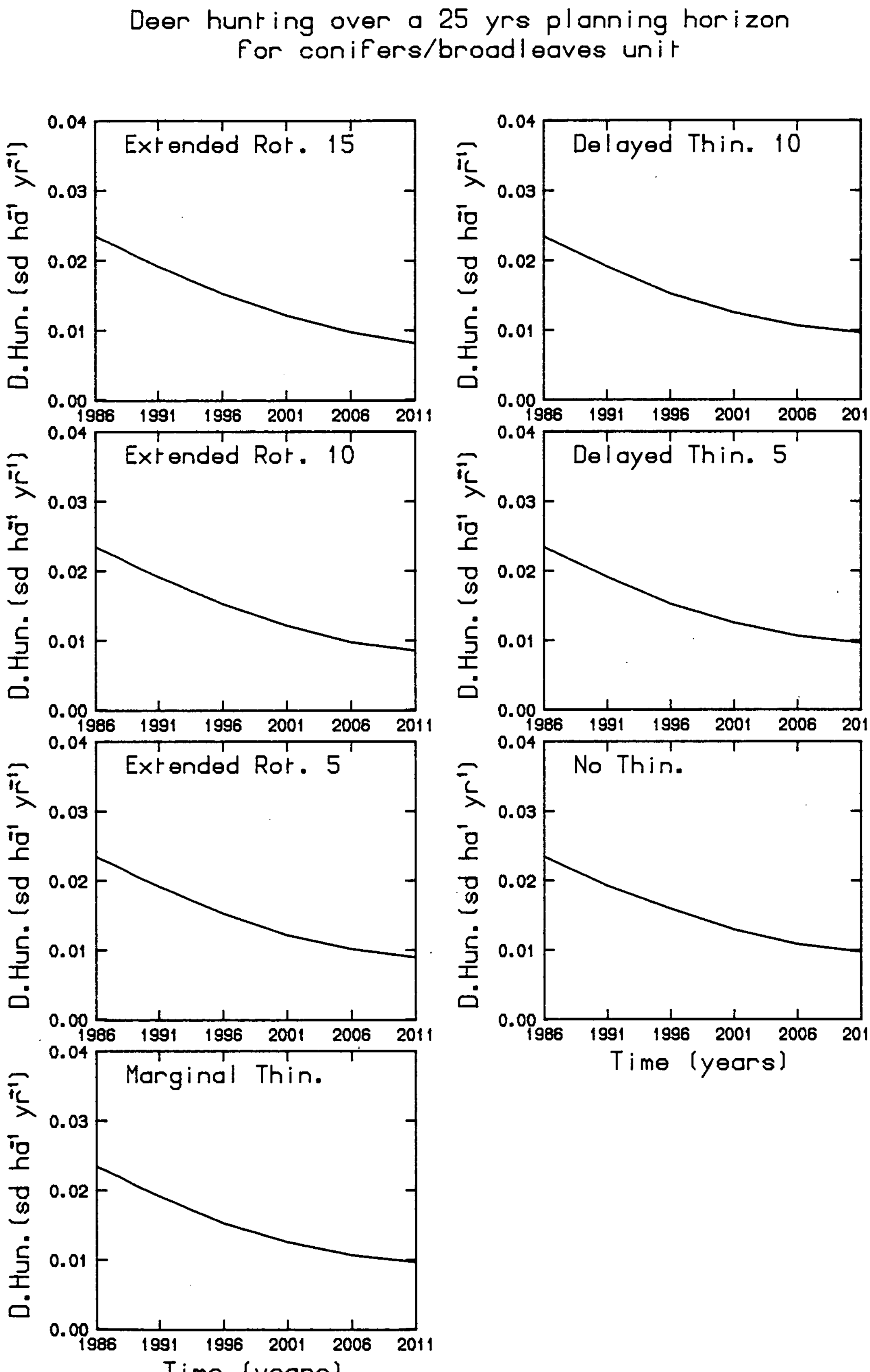

Deer hunting over a 25 yrs planning horizon
for conifers/broadleaves unit
Extended Rot. 15
Delayed Thin. 10
Extended Rot. 10
Delayed Thin. 5
Extended Rot. 5
No Thin.
Marginal Thin.
D.Hun. (sd ha⁻¹ yr⁻¹)
Time (years)

Figure 29

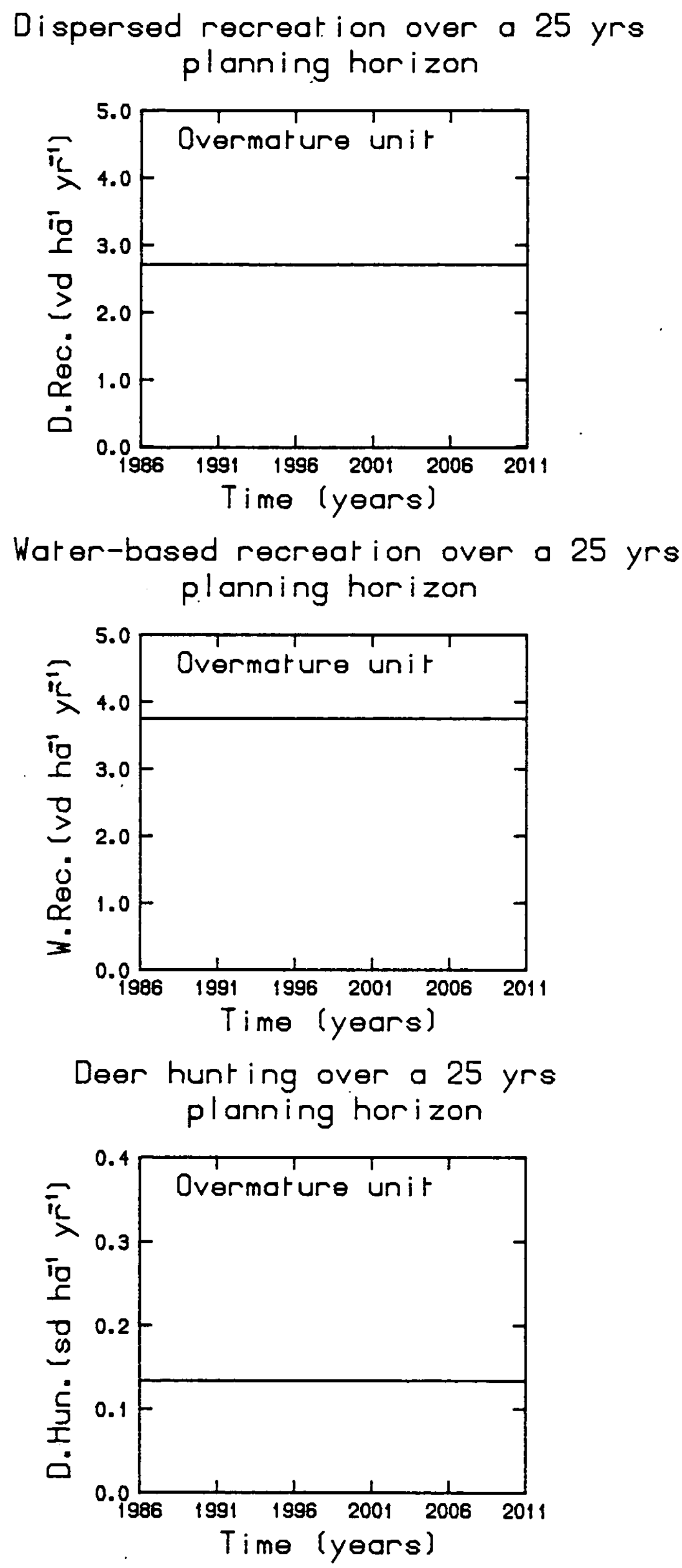

Dispersed recreation over a 25 yrs planning horizon
Overmature unit
D.Rec. (vd ha⁻¹ yr⁻¹)
5.0
4.0
3.0
2.0
1.0
0.0
1986
1991
1996
2001
2006
2011
Time (years)
Water-based recreation over a 25 yrs planning horizon
Overmature unit
W.Rec. (vd ha⁻¹ yr⁻¹)
5.0
4.0
3.0
2.0
1.0
0.0
1986
1991
1996
2001
2006
2011
Time (years)
Deer hunting over a 25 yrs planning horizon
Overmature unit
D.Hun. (sd ha⁻¹ yr⁻¹)
0.4
0.3
0.2
0.1
0.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 30

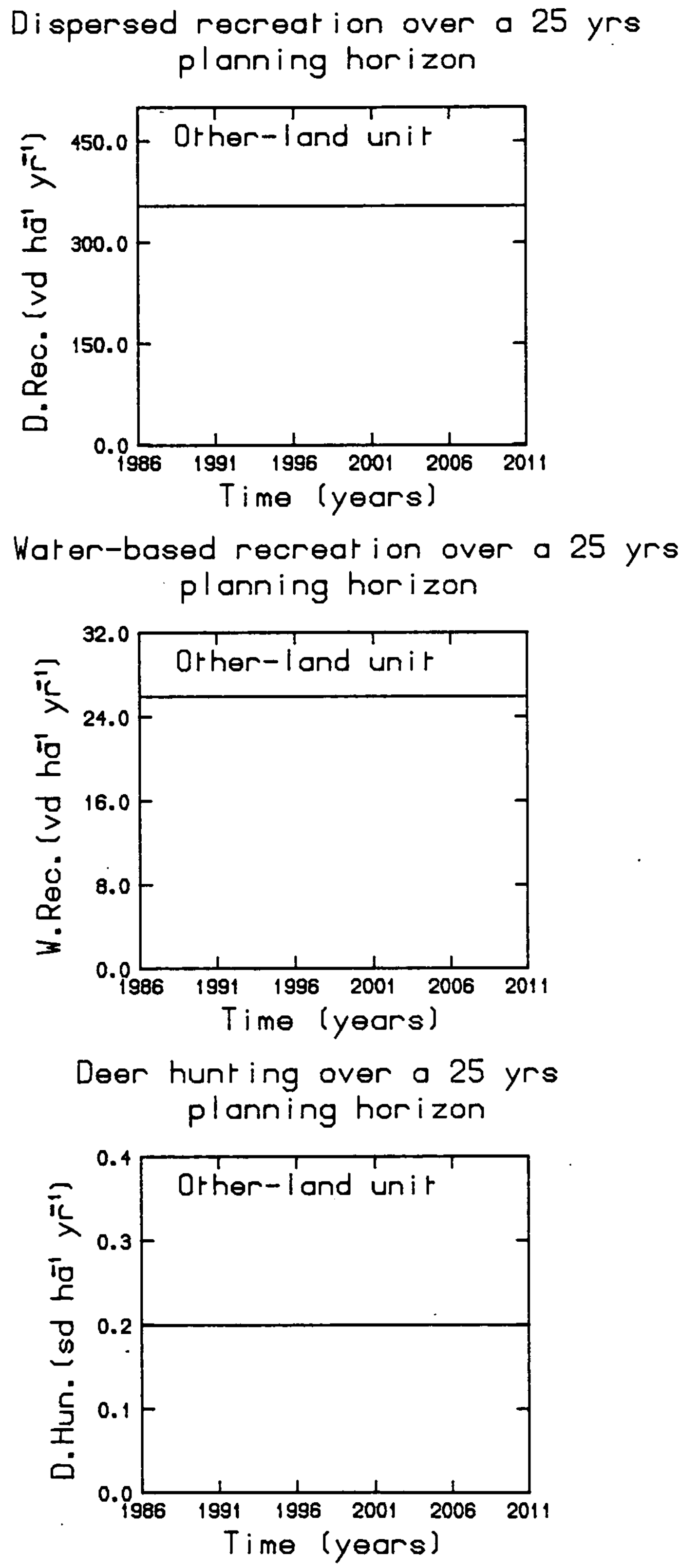

Dispersed recreation over a 25 yrs planning horizon
Other-land unit
D.Rec. (vd ha^{-1} yr^{-1})
450.0
300.0
150.0
0.0
1986
1991
1996
2001
2006
2011
Time (years)
Water-based recreation over a 25 yrs planning horizon
Other-land unit
W.Rec. (vd ha^{-1} yr^{-1})
32.0
24.0
16.0
8.0
0.0
1986
1991
1996
2001
2006
2011
Time (years)
Deer hunting over a 25 yrs planning horizon
Other-land unit
D.Hun. (sd ha^{-1} yr^{-1})
0.4
0.3
0.2
0.1
0.0
1986
1991
1996
2001
2006
2011
Time (years)

Figure 31

CHAPTER EIGHT. OPTIMIZATION MODEL OF FORM - CHOICE PHASE

8.1 INTRODUCTION

The third part of the FORM DSS consists of the choice phase. Data (technical coefficients) produced from the model base during the design phase (see chapter 7) are the input values to this component and result in trade-offs. The final adoption of the resource allocation scheme (implementation phase), which is the fourth component of FORM depends on these trade-off values.

A multi-objective procedure has been incorporated in the optimization phase to better deal with forest management multiple objectives. This procedure which is based on the MINIMAX concept has been discussed in chapter 4. An example run of the computer programs (FORM_MOP) is shown in Appendix 5. In this chapter the implementation of the method on the Queen Elizabeth Forest Park problem is presented. The method involves actively the forest manager in the solution process and proceeds in an iterative manner depending on his/her preferences. A feedback loop also makes this part of FORM a system in itself, as it allows the forest manager to change the time trajectory targets at the end of each iteration and experiment with different scenarios.

The chapter is organized as follows: Section 8.2 describes the problem along with its mathematical formulation. Section 8.3 presents the results of the Queen Elizabeth Forest Park problem. Section 8.4 provides a discussion of the results and sensitivity analysis possibilities of FORM.

8.2 FORMULATION OF THE PROBLEM.

The multi-objective problem of the Queen Elizabeth Forest case study is concerned with the selection of an optimal management plan (combination of forest management regimes) over multiple time periods, while pursuing a variety of goals, such as a desired timber yield and desired levels of dispersed recreation, water-based recreation and deer stalking , under land, budget and nature conservation constraints.

The Forest Park was divided in six management units (see chapter 6), each with a different production potential of products and services. The planning horizon was taken as 25 years, extending from year 1986 (baseline year) to year 2011 in steps of 5 years. As it has been discussed in chapter 7, any time length and step can be specified by the forest manager in the design phase.

Each of the four goals, timber production, dispersed recreation, water-based recreation and deer stalking comprises a path or trajectory of desired values over the six time periods. The target values for each of the four goals are given in Table 9.

Time Period (years)	Timber year (cu.m.'000)	Dispersed Recreation (vis.days,'000)	Water-based Recreation (vis.days,'000)	Deer Stalking (sh.days,'000)
1986	60.3	180	20	110
1991	94.5	200	22	120
1996	57.5	250	25	140
2001	97.6	250	25	150
2006	100.0	250	27	150
2011	100.0	250	27	150

Table 9. Goal Trajectory Matrix

Each of the four goal trajectories corresponds to a minimization situation and deviations from goal trajectories are measured in the MINIMAX sense. The multi-objective formulation of the problem is as follows:

* Minimize the maximum timber yield overdeviation from goal trajectory
* Minimize the maximum forest dispersed recreation overdeviation from goal trajectory
* Minimize the maximum forest water-based recreation overdeviation from goal trajectory
* Minimize the maximum deer stalking overdeviation from goal trajectory

subject to

* Timber constraints
* Forest dispersed recreation constraints
* Forest water-based recreation constraints
* Deer stalking constraints
* Area constraints
* Budget constraints
* Nature conservation constraints

Mathematically the problem can be written out as follows:

<u>Objectives:</u>

- Min α_1 timber yield over target
- Min α_2 dispersed recreation over target
- Min α_3 water-based recreation over target
- Min α_4 deer stalking over target

<u>Constraints:</u>

$$\sum_i \sum_j w_{ijt} x_{ij} - \alpha_1 = G_{1t}$$

$$\sum_i \sum_j d_{ijt} x_{ij} - \alpha_2 = G_{2t}$$

$$\sum_i \sum_j r_{ijt} x_{ij} - \alpha_3 = G_{3t}$$

$$\sum_i \sum_j s_{ijt} x_{ij} - \alpha_4 = G_{4t}$$

$$\sum_i \sum_j a_{ij} x_{ij} \leq AREA_i$$

$$\sum_i \sum_j b_{ij} x_{ij} \leq B$$

$$\sum_i \sum_j c_{ij}\, x_{ij} \leq NCA$$

$$x \geq 0$$

where, k = index forest objective functions ($k = 1,2,\ldots,4$)

i = index forest management unit ($i = 1,2,\ldots,6$)

j = forest management strategy ($j = 1,2,\ldots,30$)

t = time period of the planning horizon ($t = 1,2,\ldots,T$)

T = total number of time periods

x_{ij} = hectares of forest land management type i managed under strategy j

w_{ijt} = timber volume (m3/ha) harvested on land management type i under strategy j at time period t

d_{ijt} = dispersed recreation (visitor days/ha) on land management type i under strategy j at time period t

r_{ijt} = water-based recreation (visitor days/ha) on land management type i under strategy j at time period t

s_{ijt} = deer stalking (shooting days/ha) on land management type i under strategy j at time period t

a_{ij} = land (ha) type i under strategy j

$a_{ij} = 1.0$, if strategy j involves unit i

$a_{ij} = 0.0$, otherwise

b_{ij} = cost (£ sterling/ha) of strategy j on land management type i

c_{ij} = conservation land(ha) management type i, under strategy j

$c_{ij} = 1.0$, if management type i land includes conservation land

$c_{ij} = 0.0$, otherwise

NCA = total conservation area (ha)

B = total budget (£ sterling), $G = t \times k$ goal trajectory matrix

a_k = minimax variable associated with objective k

With T = 6 time periods, this multi-objective model has 32 constraints (six timber, six dispersed recreation, six water-based recreation, six deer stalking, four land, 1 budget and 3 nature conservation) and 34 variables (30 forest management alternative regimes and four α deviational variables).

8.3 RESULTS

With p = 6 and q = 4, the convergence factor was set r = 0.6 and the number of iterations h = 4. p represents the sample size of the final criterion vectors set to be presented to the forest manager at the end of each iteration. This is arbitrary and theoretically it could be any number. However, experience reported from applications in other fields (Silverman, Steuer and Whisman, 1985) showed that users prefer at most ' 7±2' solutions from which to make a most preferred solution. For a discussion on the q parameter see chapter 4. The final interval $[l_i, m_i]$ around the λ vector is expected to be 0.25. (1/q)

The solution process started by establishing the ideal vector $\mathbf{z}^*$. This was done by maximizing individually each objective function and setting:

$$z_i^* = \max \{ f_i(\mathbf{x}) | \mathbf{x} \in S \} + \varepsilon_i$$

ε_i was set equal to 0.000001. The ideal vector obtained was:

$$z^* = \begin{bmatrix} 120.668 \\ 270.758 \\ 28.394 \\ 172.044 \end{bmatrix}$$

The rest of the solution process was continued in an iterative manner.

<u>Iteration no. 1</u>

Using FORM_MOP_WEIVS 400 λ weighting vectors were generated randomly at the beginning of iteration 1 from the closed interval [0,1].

The program calls a random number generator subroutine for the random procedure (Legg,1973). A very low prime number is read in as a starting value and this is initially treated by dividing by 274877906944. Each time this function is called this number is multiplied by 8189 and the integer value subtracted. The result, which is a uniformly distributed random number between 0 and 1 is then used to generate the next value. The function is called twenty times at the start of each program to remove any non-random numbers typically found at the beginning of such a series. Several series can be generated simultaneously and each series can be repeated from the original starting value.

To avoid the pitfalls associated with the formation of convex combinations of efficient extreme points (see chapter 4) 50% of the weighting vectors (200) were generated from the uniform distribution, while the remaining 50% were drawn from the Weibull distribution W: b,c ~ $b(-\log R)^{1/c}$, where R was the unit rectangular variate and the value of b and c parameters were set at very low values (0.1 and 0.3 respectively).

The total number of weighting vectors was decided arbitrarily. Any number other than 400 could be generated instead. However, as 'a rule of thumb' from the literature (Steuer and Choo, 1983; Silverman et.al., 1985), a number equal to 100Xk, where k is the number of objective functions of the problem, is sufficient to guarantee a widely dispersed set of weighting values.

The next step of the solution process involved run of the FORM_MOP_SIMTEST program, which has been discussed in chapter 4. This routine reduced the set of the 400 weighting vectors to 12, the most different ones on the basis of the distance parameter d. The reduction process was necessary, because by solving all 400 MINIMAX problems, a very large amount of non-dominated solutions would have been generated, making it almost impossible for the forest manager to select the most preferred one. The size of the reduced set (12 in this case) is also arbitrary. 2Xp ('rule of thumb'), where p the size of the desired set of final solutions to be presented to the forest manager is considered sufficient. The 12 weighting vectors used at iteration 1 are shown in table 10.

FORM_MOP_MAG is a matrix generator program which was run to prepare the input values in a suitable format for the 12 MINIMAX optimization problems.

The following problem which has been presented in chapter 4 was solved for each one of the weighting vectors:

$$\min \{ \quad \alpha, \quad (z^{*}-z) \}$$

subject to

$$\alpha \geq \lambda_i (z_i^{*}-z_i) \qquad i \leq 1 \leq k$$

$$f_i(x) = z_i$$

$$x \in S$$

where, k is the number of objective functions.

Table 10. Filtered weighting vectors at iteration 1

1	0.856831	0.136107	0.002496	0.004566
2	0.653611	0.006455	0.274342	0.065592
3	0.584865	0.321276	0.001928	0.091931
4	0.475903	0.012355	0.045914	0.465829
5	0.394963	0.579979	0.000149	0.024910
6	0.394612	0.024616	0.580641	0.000131
7	0.296279	0.257012	0.000503	0.446206
8	0.241393	0.703908	0.000133	0.054566
9	0.240221	0.104664	0.636076	0.019039
10	0.124276	0.870825	0.000967	0.003932
11	0.117467	0.034999	0.549859	0.297676
12	0.024513	0.035638	0.939380	0.000469

The right hand side values of the constraint set represent the difference between the goal target vector and the ideal vector.

Optimizations were performed using FORM_MOP_MINLP. This routine was written by R.Fawcett (1974a,1974b,1974c). It is a single objective linear programming code based on the Revised Simplex Method. Its source language is IMP-80 and runs on EMAS (Edinburgh Multi-Access System) on the IBM 370-XA mainframe computer. All the other routines of FORM have been written by this author in Standard FORTRAN 77 and run also on EMAS.

After the 12 MINIMAX problems were solved, FORM_MOP_SIMTEST was run again to sample the most different 6 solutions out of the 12, which could be finally presented to the forest manager. These solutions are shown in Table 11.

As it can be seen from Table 11 each solution is described by 24 criterion values, making a total of 96 values. This was thought as a problem for the forest manager, especially if another scenario with more objective functions would be attempted. To improve upon this, graphics were introduced in FORM, drawn with the EASYGRAPH software. Two modes are presently available. Mode 1, uses histograms (figures 32,33,34). Each window refers to one time period and includes all solutions. Mode 2 draws trajectories over the planning horizon for each of the alternative solutions (Figures 35,36,37).

It was assumed at this stage (since no real forest manager was running the model), that the forest manager would select solution 5, after examining the tabular and graphic modes of the solutions. Solution 5 corresponds to alternative 2 in the graphs. FORM_MOP_WEVB was run to compute the λ vector which had solution 5 as the defining point of the the corresponding MINIMAX program isoquant, and the bounds $[l_i,m_i]$ around this vector (see chapter 4). λ^1 and $[l_i,m_i]^1$ are shown below:

$$\lambda^1 = \begin{bmatrix} 0.058922 \\ 0.142554 \\ 0.178519 \\ 0.620005 \end{bmatrix}$$

$$[l_i,m_i]^1 = [0.000000, 0.600000]$$

$$[l_i,m_i]^1 = [0.000000, 0.600000]$$

$$[l_i,m_i]^1 = [0.000000, 0.600000]$$

$$[l_i,m_i]^1 = [0.320005, 0.920005]$$

At this stage iteration 1 was finished and iteration 2 started to sample more carefully the non-dominated criterion vectors in the neighbourhood of solution 5.

Iteration 2

400 λ weighting vectors were generated from the closed interval $[l_i,m_i]^1$, by running FORM_MOP_WEIVS. These using FORM_MOP_SIMTEST were reduced to 12, shown in Table 15.

The 12 MINIMAX problems were solved with the FORM_MOP_MINLP code and were reduced to 6 with the FORM_MOP_SIMTEST. The second round criterion vectors in tabular and graphical form (mode 1 and mode 2) are shown in Table 12 and figures 38,39,40,41,42,43.

Solution 8, which corresponds to alternative 3 in the graphs, was selected as the most preferred at this iteration and FORM_MOP_WEVD was run to compute the weighting vector which has solution 8 as the defining point of the corresponding MINIMAX program isoquant:

Table 11. Alternative solutions at iteration 1

		TIMBER	D.REC.	W.REC.	D.HUN.
Sol. 1	Period 1	112.8372	258.3223	19.0913	175.7204
Sol. 1	Period 2	123.1517	258.3379	19.1069	171.6800
Sol. 1	Period 3	122.6685	258.3582	19.1413	169.5533
Sol. 1	Period 4	119.8470	258.4238	19.1491	169.5221
Sol. 1	Period 5	117.3955	258.5662	19.1788	170.8740
Sol. 1	Period 6	108.4526	259.0977	19.2007	172.5679
Sol. 5	Period 1	91.1004	258.9846	19.8583	173.7171
Sol. 5	Period 2	103.0112	259.1165	19.9902	169.9386
Sol. 5	Period 3	100.0823	259.2878	20.2802	167.8694
Sol. 5	Period 4	98.0087	259.8418	20.3461	167.6323
Sol. 5	Period 5	96.2210	261.0415	20.5966	168.8188
Sol. 5	Period 6	88.6056	265.5242	20.7812	170.3199
Sol. 6	Period 1	104.6273	258.7354	19.4694	174.0928
Sol. 6	Period 2	111.3552	258.8398	20.1808	170.2611
Sol. 6	Period 3	112.1351	258.9968	20.3273	168.2362
Sol. 6	Period 4	108.9812	259.1487	20.4057	168.2166
Sol. 6	Period 5	106.5444	259.1277	20.4580	169.4284
Sol. 6	Period 6	98.4966	259.1067	20.0605	171.0073
Sol. 8	Period 1	76.1632	259.5728	20.6980	172.0171
Sol. 8	Period 2	85.9158	259.8757	20.9846	168.4241
Sol. 8	Period 3	83.5155	260.2766	21.4788	166.3872
Sol. 8	Period 4	81.7919	261.4326	21.5695	166.0088
Sol. 8	Period 5	80.2809	263.5793	21.9662	166.9477
Sol. 8	Period 6	74.0408	268.4956	22.0508	168.2371
Sol. 10	Period 1	51.6455	260.5872	22.1852	169.1137
Sol. 10	Period 2	56.7043	261.2024	22.7513	165.8297
Sol. 10	Period 3	55.8384	262.0222	23.5924	163.8463
Sol. 10	Period 4	54.5741	264.2585	23.7193	163.2401
Sol. 10	Period 5	53.4432	268.0405	24.3560	163.7361
Sol. 10	Period 6	49.5980	272.9570	24.2085	164.6563
Sol. 11	Period 1	83.2873	259.4626	20.1664	170.9795
Sol. 11	Period 2	90.0258	259.7187	21.9082	167.6258
Sol. 11	Period 3	89.8479	260.1030	22.2668	165.8511
Sol. 11	Period 4	87.4687	260.4744	22.4589	165.8329
Sol. 11	Period 5	85.7081	260.4233	22.5870	166.9777
Sol. 11	Period 6	79.1747	260.3721	21.6137	168.4675

Table 12. Alternative solutions at iteration 2

		TIMBER	D.REC.	W.REC.	D.HUN.
Sol. 1	Period 1	112.8372	258.3223	19.0913	175.7204
Sol. 1	Period 2	123.1517	258.3379	19.1069	171.6800
Sol. 1	Period 3	122.6685	258.3582	19.1413	169.5533
Sol. 1	Period 4	119.8470	258.4238	19.1491	169.5221
Sol. 1	Period 5	117.3955	258.5662	19.1788	170.8740
Sol. 1	Period 6	108.4526	259.0977	19.2007	172.5679
Sol. 5	Period 1	94.1424	258.8955	19.7552	173.9930
Sol. 5	Period 2	105.7759	259.0117	19.8714	170.1795
Sol. 5	Period 3	103.1544	259.1628	20.1271	168.1040
Sol. 5	Period 4	100.9378	259.6511	20.1852	167.8982
Sol. 5	Period 5	99.0477	260.7085	20.4060	169.1127
Sol. 5	Period 6	91.2378	264.6602	20.5687	170.6431
Sol. 8	Period 1	68.7320	259.8801	21.1488	171.1371
Sol. 8	Period 2	77.0620	260.2781	21.5200	167.6377
Sol. 8	Period 3	75.1267	260.8057	22.1195	165.6171
Sol. 8	Period 4	73.5424	262.2893	22.2211	165.1696
Sol. 8	Period 5	72.1465	264.9316	22.6906	165.9743
Sol. 8	Period 6	66.6323	269.8479	22.7048	167.1518
Sol. 9	Period 1	85.1403	259.3950	20.1016	171.2589
Sol. 9	Period 2	92.0207	259.6372	21.7477	167.8652
Sol. 9	Period 3	91.8428	260.0002	22.0866	166.0710
Sol. 9	Period 4	89.4121	260.3513	22.2681	166.0550
Sol. 9	Period 5	87.6012	260.3027	22.3892	167.2143
Sol. 9	Period 6	80.9190	260.2544	21.4693	168.7180
Sol. 11	Period 1	46.2009	260.8125	22.5155	168.4690
Sol. 11	Period 2	50.2174	261.4971	22.1436	165.2536
Sol. 11	Period 3	49.6922	262.4099	24.0617	163.2821
Sol. 11	Period 4	48.5299	264.8860	24.1967	162.6252
Sol. 11	Period 5	47.4834	269.0315	24.8867	163.0231
Sol. 11	Period 6	44.1700	273.9478	24.6877	163.8612
Sol. 12	Period 1	4.6186	262.4080	24.8546	163.6724
Sol. 12	Period 2	4.5706	263.5837	25.9224	161.0453
Sol. 12	Period 3	4.3906	265.1553	27.3859	159.2459
Sol. 12	Period 4	4.4266	269.3303	27.5779	158.2863
Sol. 12	Period 5	4.2707	276.0483	28.6455	158.1784
Sol. 12	Period 6	4.5346	280.9646	28.0815	158.5624

Table 13. Alternative solutions at iteration 3

		TIMBER	D.REC.	W.REC.	D.HUN.
Sol. 1	Period 1	112.8372	258.3223	19.0913	175.7204
Sol. 1	Period 2	123.1517	258.3379	19.1069	171.6800
Sol. 1	Period 3	122.6685	258.3582	19.1413	169.5533
Sol. 1	Period 4	119.8470	258.4238	19.1491	169.5221
Sol. 1	Period 5	117.3955	258.5662	19.1788	170.8740
Sol. 1	Period 6	108.4526	259.0977	19.2007	172.5679
Sol. 7	Period 1	79.6541	259.4282	20.4862	172.4305
Sol. 7	Period 2	90.0751	259.6870	20.7330	168.7935
Sol. 7	Period 3	87.4563	260.0281	21.1779	166.7490
Sol. 7	Period 4	85.6673	261.0303	21.2635	166.4030
Sol. 7	Period 5	84.1022	262.9441	21.6260	167.4049
Sol. 7	Period 6	77.5211	267.8604	21.7435	168.7468
Sol. 8	Period 1	94.8985	259.0530	19.7739	172.7018
Sol. 8	Period 2	102.0784	259.2239	20.9354	169.0928
Sol. 8	Period 3	102.1611	259.4800	21.1745	167.1889
Sol. 8	Period 4	99.4098	259.7278	21.3026	167.1775
Sol. 8	Period 5	97.3079	259.6936	21.3880	168.3858
Sol. 8	Period 6	89.8960	259.6594	20.7389	169.9429
Sol. 10	Period 1	56.8106	260.3735	21.8719	169.7254
Sol. 10	Period 2	62.8582	260.9231	22.3791	166.3763
Sol. 10	Period 3	61.6691	261.6545	23.1471	164.3816
Sol. 10	Period 4	60.3080	263.6631	23.2664	163.8233
Sol. 10	Period 5	59.0970	267.1008	23.8526	164.4128
Sol. 10	Period 6	54.7473	272.0171	23.7540	165.4107
Sol. 11	Period 1	64.9457	260.1345	20.8397	168.2557
Sol. 11	Period 2	70.2712	260.5371	23.4754	165.2905
Sol. 11	Period 3	70.0933	261.1384	24.0321	163.7024
Sol. 11	Period 4	68.2281	261.7556	24.3225	163.6563
Sol. 11	Period 5	66.9583	261.7622	24.5264	164.6567
Sol. 11	Period 6	61.9034	261.6252	23.0455	166.0092
Sol. 12	Period 1	4.6186	262.4080	24.8546	163.6724
Sol. 12	Period 2	4.5706	263.5837	25.9224	161.0453
Sol. 12	Period 3	4.3906	265.1553	27.3859	159.2459
Sol. 12	Period 4	4.4266	269.3303	27.5779	158.2863
Sol. 12	Period 5	4.2707	276.0483	28.6455	158.1784
Sol. 12	Period 6	4.5346	280.9646	28.0815	158.5624

Table 14. Alternative solutions at iteration 4

		TIMBER	D.REC.	W.REC.	D.HUN.
Sol. 1	Period 1	112.8372	258.3223	19.0913	175.7204
Sol. 1	Period 2	123.1517	258.3379	19.1069	171.6800
Sol. 1	Period 3	122.6685	258.3582	19.1413	169.5533
Sol. 1	Period 4	119.8470	258.4238	19.1491	169.5221
Sol. 1	Period 5	117.3955	258.5662	19.1788	170.8740
Sol. 1	Period 6	108.4526	259.0977	19.2007	172.5679
Sol. 6	Period 1	92.8778	259.0127	19.8397	173.4428
Sol. 6	Period 2	102.4340	259.1577	20.2934	169.6919
Sol. 6	Period 3	100.9822	259.3569	20.5702	167.6508
Sol. 6	Period 4	98.5788	259.8203	20.6560	167.4665
Sol. 6	Period 5	96.6213	260.6465	20.8573	168.6060
Sol. 6	Period 6	89.1353	263.7617	20.7839	170.0879
Sol. 7	Period 1	70.9225	259.7896	21.0159	171.3965
Sol. 7	Period 2	79.6717	260.1594	21.3622	167.8696
Sol. 7	Period 3	77.5994	260.6499	21.9306	165.8441
Sol. 7	Period 4	75.9740	262.0366	22.0291	165.4169
Sol. 7	Period 5	74.5442	264.5330	22.4771	166.2613
Sol. 7	Period 6	68.8161	269.4492	22.5120	167.4717
Sol. 8	Period 1	39.4611	260.8723	22.6031	167.8945
Sol. 8	Period 2	49.0185	261.5752	23.2477	164.8766
Sol. 8	Period 3	44.9578	262.5127	24.1863	163.0625
Sol. 8	Period 4	44.6569	265.0525	24.3234	162.4896
Sol. 8	Period 5	44.1461	269.2944	25.0276	163.1956
Sol. 8	Period 6	40.6417	274.2107	24.8149	164.2343
Sol. 11	Period 1	78.3799	259.1829	20.0878	172.6201
Sol. 11	Period 2	97.2748	259.3496	20.2544	169.1259
Sol. 11	Period 3	89.6783	259.5662	20.6210	167.2480
Sol. 11	Period 4	88.9512	260.2659	20.7043	167.0512
Sol. 11	Period 5	88.0689	261.8572	21.0961	168.5711
Sol. 11	Period 6	80.6542	266.0942	20.5626	170.3229
Sol. 12	Period 1	21.7411	261.8403	23.7604	163.5681
Sol. 12	Period 2	23.3547	262.8816	26.2690	161.1991
Sol. 12	Period 3	23.1768	264.3247	27.4177	159.7996
Sol. 12	Period 4	22.6946	267.3298	27.6785	159.4699
Sol. 12	Period 5	22.3102	271.0222	28.3180	160.0632
Sol. 12	Period 6	20.9347	268.2930	26.5550	161.0333

Table 15. Filtered weighting vectors at iteration 2

1	0.856831	0.136107	0.002496	0.004566
2	0.582111	0.278023	0.139204	0.000662
3	0.534031	0.010591	0.440092	0.015286
4	0.472130	0.144374	0.127548	0.255949
5	0.346764	0.427254	0.223365	0.002618
6	0.317627	0.052332	0.629688	0.000353
7	0.307193	0.281409	0.130705	0.280693
8	0.200950	0.775808	0.018986	0.004256
9	0.181094	0.012103	0.780047	0.026755
10	0.129528	0.226951	0.134830	0.508692
11	0.097536	0.826021	0.042549	0.033894
12	0.003419	0.576900	0.412377	0.007303

$$\boldsymbol{\lambda}^{2} = \begin{bmatrix} 0.059545 \\ 0.181645 \\ 0.291323 \\ 0.467486 \end{bmatrix}$$

and the bounds $[l_i,m_i]^2$ about $\boldsymbol{\lambda}^2$:

$[l_i,m_i]^2 = [0.000000, 0.360000]$

$[l_i,m_i]^2 = [0.000000, 0.360000]$

$[l_i,m_i]^2 = [0.000000, 0.360000]$

$[l_i,m_i]^2 = [0.038543, 0.398543]$

Iteration 2 was ended at this stage and iteration 3 was started for an exploration of the neighbourhood of solution 8.

Iteration 3

The same process was repeated as in the previous two iterations. 400 weighting vectors were generated from $[l_i,m_i]^2$ and reduced to 12 shown in Table 16.

Table 16. Filtered weighting vectors at iteration 3

1	0.719558	0.114302	0.158446	0.007695
2	0.432425	0.165712	0.196323	0.205541
3	0.697781	0.021965	0.021330	0.258924
4	0.402577	0.513235	0.024437	0.059751
5	0.347290	0.040991	0.566354	0.045366
6	0.284148	0.123837	0.084642	0.507373
7	0.246965	0.625040	0.048845	0.079150
8	0.205411	0.118718	0.550148	0.125721
9	0.159757	0.031637	0.038797	0.769809
10	0.126840	0.744104	0.082892	0.046165
11	0.086315	0.046455	0.842019	0.025211
12	0.004166	0.976755	0.010393	0.008686

The 12 solutions which were derived by solving the 12 MINIMAX problems were reduced to 6. These are shown in tabular and graphical form in Table 13 and Figures 44,45,46,47,48,49 respectively.

Solution 7, which corresponds to alternative 2 in the graphs was considered as the most preferred. With $\boldsymbol{\lambda}^3$ of the solution 7 MINIMAX isoquant:

$$\boldsymbol{\lambda}^3 = \begin{bmatrix} 0.049361 \\ 0.202287 \\ 0.250001 \\ 0.498351 \end{bmatrix}$$

the bounds $[l_i,m_i]^3$ about $\boldsymbol{\lambda}^3$ were:

$$[l_i,m_i]^3 = [0.000000, 0.216000]$$

$$[l_i,m_i]^3 = [0.000000, 0.216000]$$

$$[l_i,m_i]^3 = [0.000000, 0.216000]$$

$$[l_i,m_i]^3 = [0.015767, 0.231767]$$

The algorithm could be terminated at this point, since the width of $[l_i,m_i]^3$ is equal to 0.216000, which is $\leq 1/q = 1/4$. However, it was decided to continue for one more iteration in an attempt to increase more the degree of resolution of the final solution. The weighting vectors and the final solutions in tabular and graphical form of iteration 4 are shown in Tables 17 and 14 and Figures 50,51,52,53,54,55.

Table 17. Filtered weighting vectors at iteration 4

1	0.687016	0.109132	0.151280	0.052572
2	0.580938	0.071124	0.067140	0.280798
3	0.420834	0.119623	0.337864	0.121679
4	0.390337	0.391400	0.166075	0.052188
5	0.317277	0.198293	0.069688	0.414742
6	0.141070	0.180886	0.370235	0.307809
7	0.125056	0.445513	0.269383	0.160048
8	0.033711	0.460693	0.081071	0.424525
9	0.134632	0.190036	0.604958	0.070373
10	0.035570	0.707088	0.133803	0.123539
11	0.050257	0.120649	0.222530	0.606564
12	0.016432	0.041757	0.889529	0.052282

Solution 11, which corresponds to alternative 5 in the graphs was selected as the final preferred solution. λ^4 and $[l_i,m_i]^4$ were as follows:

$$\lambda^4 = \begin{bmatrix} 0.058461 \\ 0.184405 \\ 0.297926 \\ 0.459208 \end{bmatrix}$$

$$[l_i,m_i]^4 = [0.000000, 0.129600]$$

$$[l_i,m_i]^4 = [0.000000, 0.129600]$$

$$[l_i,m_i]^4 = [0.000000, 0.129600]$$

$$[l_i,m_i]^4 = [0.000000, 0.129600]$$

At this stage the solution process was finalized. The inverse image of the final solution no. 11 of iteration 4 was the following:

$x_1 = 0.0$, $x_2 = 0.0$, $x_3 = 1{,}503.351$, $x_4 = 162.848$, $x_5 = 0.0$, $x_6 = 0.0$,

$x_7 = 177.406$, $x_8 = 0.0$, $x_9 = 0.0$, $x_{10} = 0.0$, $x_{11} = 0.0$, $x_{12} = 0.0$, $x_{13} = 0.0$,

$x_{14} = 7{,}638.9$, $x_{15} = 0.0$, $x_{16} = 0.0$, $x_{17} = 0.0$, $x_{18} = 0.0$, $x_{19} = 0.0$,

$x_{20} = 0.0$, $x_{21} = 48.970$, $x_{22} = 0.0$, $x_{23} = 0.0$, $x_{24} = 0.0$, $x_{25} = 0.0$,

$x_{26} = 0.0$, $x_{27} = 0.0$, $x_{28} = 0.0$, $x_{29} = 224.9$, $x_{30} = 7{,}299.2$

8.3 DISCUSSION OF RESULTS-SENSITIVITY ANALYSIS

The preceding illustration was tentative. There was no real forest manager during the solution process due to time limits within which this work should be completed. However, this discussion will highlight some points in relation to the interpretation aspects of the values resulted from these example runs.

Selection of preferred alternatives was based on the assumption that the real forest manager would favour achievement of the timber goal at the expense of the other goals, that is timber production was ranked implicitly as a higher priority goal. It is believed that this would comply with the present policy of the British Forestry Commission which values timber production more than other goals even in a 'multiple use' context. The data used in this application , however, are real extracted from unpublished reports of the Aberfoyle Forest District Office and several meetings with the district forest manager.

The final solution indicates that there is no problem in meeting the dispersed recreation and deer hunting goals, with a working capital of £200,000 and the nature conservation constraints. Indeed from year 1986 until year 1996 the achieved values appear much higher than the specified ones, while from year 1996 until the end of the planning horizon, the achieved values are much closer to the specified targets, but still higher. This suggests that these two goals can be increased to some extent.

Also no problem appears in meeting the timber production goal from year 1986 until year 2001. However, from year 2001 until the end of the planning horizon the specified targets can not be achieved within the budget and conservation constraints.

The water-based recreation presents a problem, as with the exception of year 1986 was not achieved throughout the planning period.

The resource allocation scheme, which results by adopting solution no.11 (alternative 5 in the graphs) at the final iteration suggests: 1,503.351 hectares of spruces land to be managed under the extended rotation by 10 years marginal thinning regime (x_3), 162.848 hectares of spruces land under the extended rotation by 15 years marginal thinning regime (x_4), 177.406 hectares of spruces land under the non-thinning regime (x_7), 7,638.9 hectares of spruces/pines/larches land under the non-thinning regime (x_{14}), 48.97 hectares of mixed conifers under the non-thinning regime (x_{21}) and retain 224.9 and 7,299.2 hectares of land under overmature growth and other land habitat types respectively (x_{29} and x_{30}).

The deviational variables for the four goals in each time period were found as follows:

- Timber Period 1 (1986) = 400 m^3
- Timber Period 2 (1991) = 300 m^3
- Timber Period 3 (1996) = 380 m^3
- Timber Period 4 (2001) = 360 m^3
- Timber Period 5 (2006) = 350 m^3
- Timber Period 6 (2011) = 340 m^3

- Dispersed Recreation Period 1 (1986) = 30 vis. days
- Dispersed Recreation Period 2 (1991) = 50 vis. days
- Dispersed Recreation Period 3 (1996) = 60 vis. days
- Dispersed Recreation Period 4 (2001) = 110 vis. days
- Dispersed Recreation Period 5 (2006) = 160 vis. days
- Dispersed Recreation Period 6 (2011) = 170 vis. days

- Water-based Recreation Period 1 (1986) = 60 vis.days
- Water-based Recreation Period 2 (1991) = 80 vis.days
- Water-based Recreation Period 3 (1996) = 90 vis.days
- Water-based Recreation Period 4 (2001) = 90 vis.days
- Water-based Recreation Period 5 (2006) = 90 vis.days
- Water-based Recreation Period 6 (2011) = 90 vis.days
- Deer stalking Period 1 (1986) = 30 sh.days

- Deer stalking Period 2 (1991) = 30 sh.days
- Deer stalking Period 3 (1996) = 30 sh.days
- Deer stalking Period 4 (2001) = 30 sh.days
- Deer stalking Period 5 (2006) = 30 sh.days
- Deer stalking Period 6 (2011) = 30 sh.days

Degeneracy was observed during examination of the results, since most of the goal constraint variables were at zero value in the basis. This, however, was expected and was not considered as a problem, because all goals were 'forced' to equality levels in the system.

Sensitivity analysis was performed with FORM_MOP_MINLP. For the final solution selected, spruces , conifers/broadleaves, nature conservation and mixed conifers land appear to be slack resources with 1,130, 400, 6,500 and 1,880 hectares of idle land respectively. The marginal value of these land type restraints is apparently zero. This suggests that the optimal solution can be implemented without intensive management.

Spruces/pines/larches, overmature growth and other land and budget restraints are binding. The marginal unit of spruces/pines/larches land exactly combines with the substitution of :

$$(0.61799)x_3 + (-0.43103)x_4 + (-0.414019)\ x_7 + (1.0)x_{14} + (-0.766567)x_{21} + (0.0)x_{29} + (0.0)x_{30}$$

to yield a further decrease in the overall maximum overdeviation of the goal targets of 0.000576 and have no slack resource.

The marginal unit of overmature land combines with the substitution of:

$$(20.44)\ x_3 + (-14.13)x_4 + (-7.71)x_7 + (0.0)x_{14} + (-2.575)\ x_{21} + (1.0)x_{29} + (0.0)x_{30}$$

to yield an extra decrease in the maximum overdeviation of the goal targets of 0.020207 an have no slack resource.

The marginal unit of other land habitat type can yield a further decrease in the overall maximum overdeviation of the goal targets of 0.038448 with the substitution of :

$$(62.20)\ x_3 + (-52.71)x_4 + (-9.9669)\ x_7 + (0.0)x_{14} + (-5.0312)x_{21} + (0.0)\ x_{29} + (0.0)x_{30}.$$

Finally the marginal unit of the working capital exactly combines with the substitution of:

$(0.178)x_3 + (-0.1243)x_4 + (-0.0564)x_7 + (0.0)x_{14} + (0.0142)x_{21} + (0.0)x_{29}$

$+ (0.0)\ x_{30}$

to yield a further decrease in the maximum overdeviation of the goal targets of 0.000166.

Another possibility of the sensitivity analysis is to find the extent of increase and decrease for the limiting resources before the basis of the solution is altered.

For the spruces/pines/larches land restraint 2,430 hectares of land have to be withdrawn before variable x_3 (extended marginal thinning regime of spruces unit) can be driven out of the solution. Similarly, for the overmature growth and other land habitat land restraints 70 and 30 hectares must be withdrawn respectively to driving x_3 out of the solution. Each unit withdrawn would reduce the maximum overdeviation of the goal targets by the shadow price. For the spruces/pines/larches and nature conservation land restraints the shadow price is zero, while for the overmature and other land restraints is 20 and 40 hectares respectively.

For the nature conservation restraint 3,450 ha have to be withdrawn before driving x_{21} (non-thinning regime of mixed conifers land) out of the solution at zero marginal value product.

For the expansion of the quantity of a resource, an increase in the maximum overdeviation of the goal targets by the marginal value product occurs for each unit of the resource. 20 hectares of spruces/pines/larches land is required to drive the timber period 1 (1986) deviational variable out of the solution. The increase and decrease in units for the four goals in each time period is as follows:

-For timber,

period 1	0 m^3	increase	or	400 m^3	decrease
period 2	100 m^3	increase	or	300 m^3	decrease
period 3	20 m^3	increase	or	380 m^3	decrease
period 4	40 m^3	increase	or	360 m^3	decrease
period 5	50 m^3	increase	or	350 m^3	decrease
period 6	70 m^3	increase	or	340 m^3	decrease

would drive the corresponding deviational variables out at the optimal solution.

-For dispersed recreation,

period 1	30 v.d.	increase	or	130 v.d.	decrease
period 2	50 v.d.	increase	or	120 v.d.	decrease

period 3	60 v.d.	increase	or	100 v.d.	decrease
period 4	110 v.d.	increase	or	60 v.d.	decrease
period 5	10 v.d.	increase	or	160 v.d.	decrease

would drive the corresponding deviational variables out at the optimal solution, while for dispersed recreation,

period 5 0 v.d. increase or 10 v.d. decrease

would drive x_4 (extended by 15 years marginal thinning regime of spruces land) and x_3 (extended by 15 years marginal thinning regime of spruces unit) respectively out.

For water-based recreation,

period 1	40 v.d.	increase	or	60 v.d.	decrease
period 2	20 v.d.	increase	or	80 v.d.	decrease
period 3	10 v.d.	increase	or	90 v.d.	decrease
period 4	0 v.d.	increase	or	90 v.d.	decrease
period 6	20 v.d.	increase	or	80 v.d.	decrease

would drive the corresponding deviational variables out at the optimal solution, while for water-based recreation,

period 5 0 v.d. increase or 0 v.d. decrease would drive x_4 (extended by 15 years marginal thinning regime of spruces land) out.

For deer stalking,

period 1 0 s.d. increase or 0 s.d. decrease would drive x_{21} (non-thinning regime of mixed conifers land) out, while for deer stalking,

period 2	10 s.d.	increase	or	30 s.d.	decrease
period 3	30 s.d.	increase	or	10 s.d.	decrease
period 4	10 s.d.	increase	or	30 s.d.	decrease
period 5	10 s.d.	increase	or	30 s.d.	decrease
period 6	0 s.d.	increase	or	0 s.d.	decrease

would drive the corresponding deviational variables out at the optimal solution.

The units and substitution of bringing an excluded regime in the solution is shown on the next page:

NON BAS. VARIABLES		UNITS IN	BAS.VARIABLES OUT
SPR D10	- x_1	80 ha	Timber deviational 1
SPR D5	- x_2	260 ha	Timber deviational 1
SPR EXR5	- x_5	190 ha	Timber deviational 1
SPR MT	- x_6	200 ha	Timber deviational 4
SRLRPI D10	- x_8	470 ha	x_3- SPR EXR10
SRLRPI D5	- x_9	380 ha	x_3- SPR EXR10
SRLRPI EXR10	- x_{10}	290 ha	x_3- SPR EXR10
SRLRPI EXR15	- x_{11}	270 ha	x_3- SPR EXR10
SRLRPI EXR5	- x_{12}	330 ha	x_3- SPR EXR10
SRLRPI MT	- x_{13}	390 ha	x_3- SPR EXR10
MICO D10	- x_{15}	50 ha	x_{21}- MICO NT
MICO D5	- x_{16}	50 ha	x_{21}- MICO NT
MICO EXR10	- x_{17}	70 ha	x_{21}- MICO NT
MICO EXR15	- x_{18}	90 ha	x_{21}- MICO NT
MICO EXR5	- x_{19}	50 ha	x_{21}- MICO NT
MICO MT	- x_{20}	40 ha	x_{21}- MICO NT
COBRD D10	- x_{22}	400 ha	MICO land restraint
COBRD D5	- x_{23}	400 ha	MICO land restraint
COBRD EXR10	- x_{24}	400 ha	MICO land restraint
COBRD EXR15	- x_{25}	400 ha	MICO land restraint
COBRD EXR5	- x_{26}	400 ha	MICO land restraint
COBRD MT	- x_{27}	400 ha	MICO land restraint
COBRD NT	- x_{28}	20 ha	Timber deviational 1

Notation:

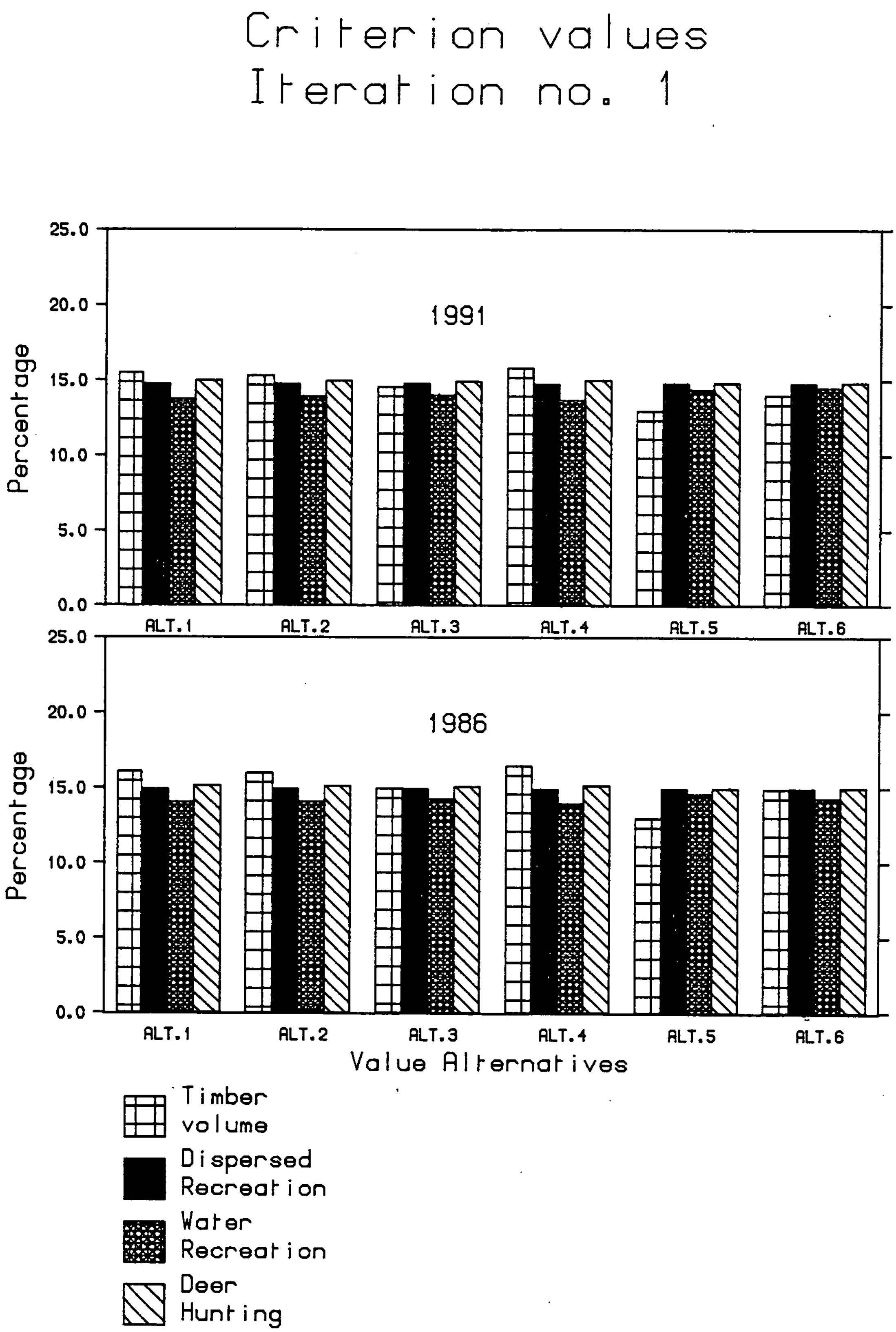
SPR: Spruces habitat land

SRLRPI: Spruces/pines/larches habitat land

MICO: Mixed conifers habitat land

COBRD: Conifers/broadleaves habitat land

At this stage the sensitivity analysis was completed and the solution process was terminated. The forest manager can change the goal target values at the end of each iteration if managerial conditions or preference changes have occurred. In this case the solution process re-starts from STEP 1 by re-computing the ideal vector and continues in the same manner described in the preceding sections.



Criterion values
Iteration no. 1
1991
1986
Percentage
25.0
20.0
15.0
10.0
5.0
0.0
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 32

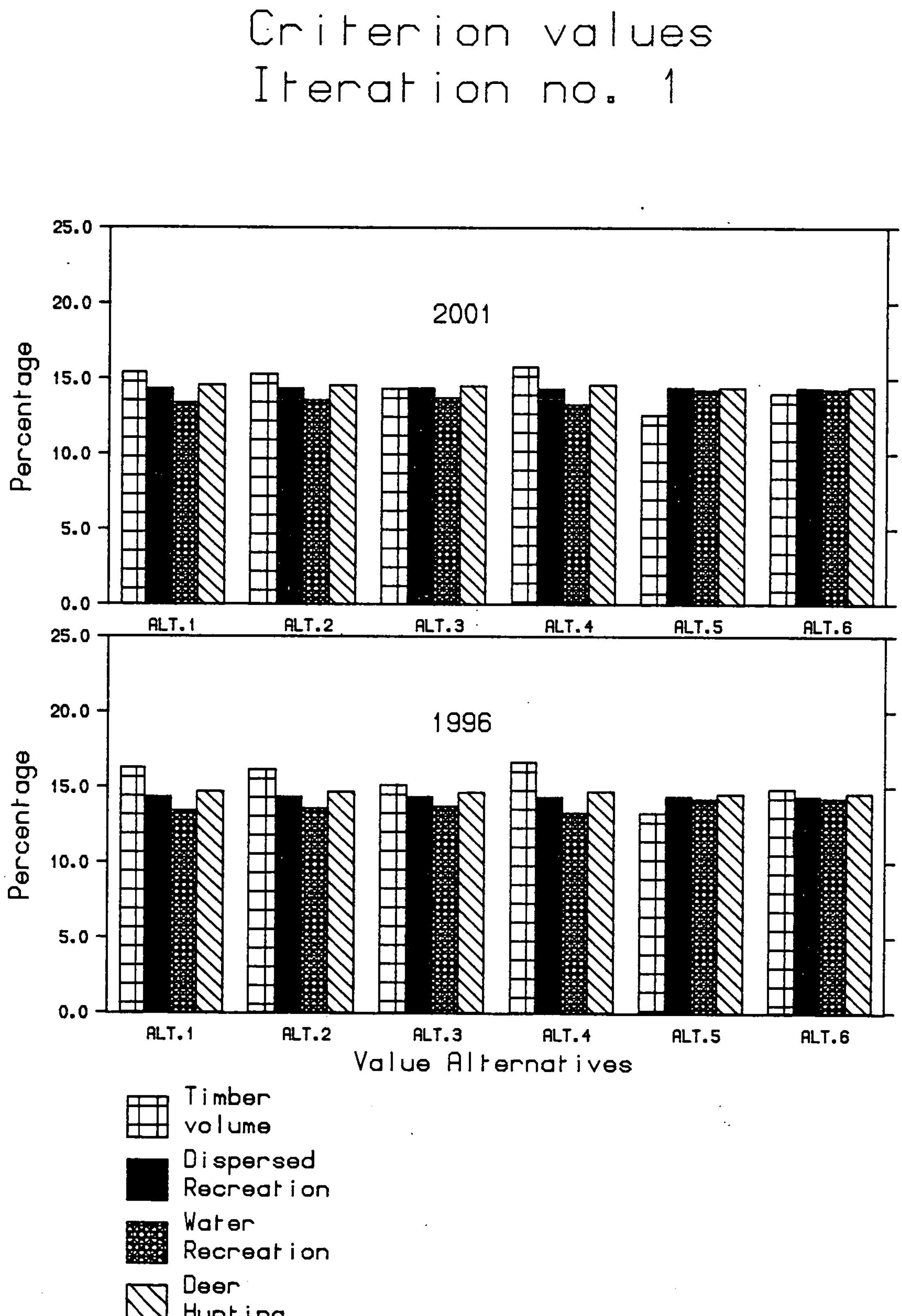
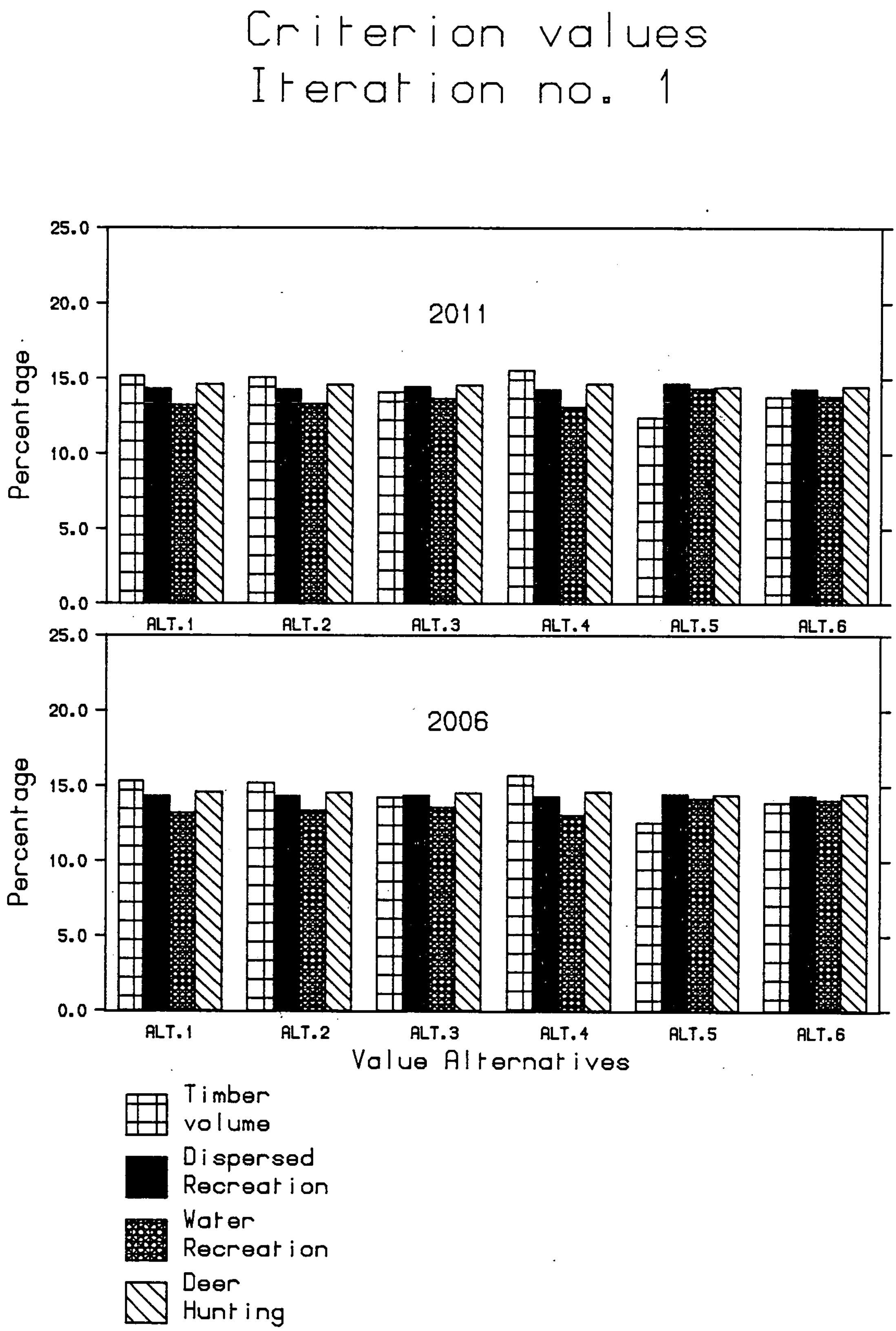
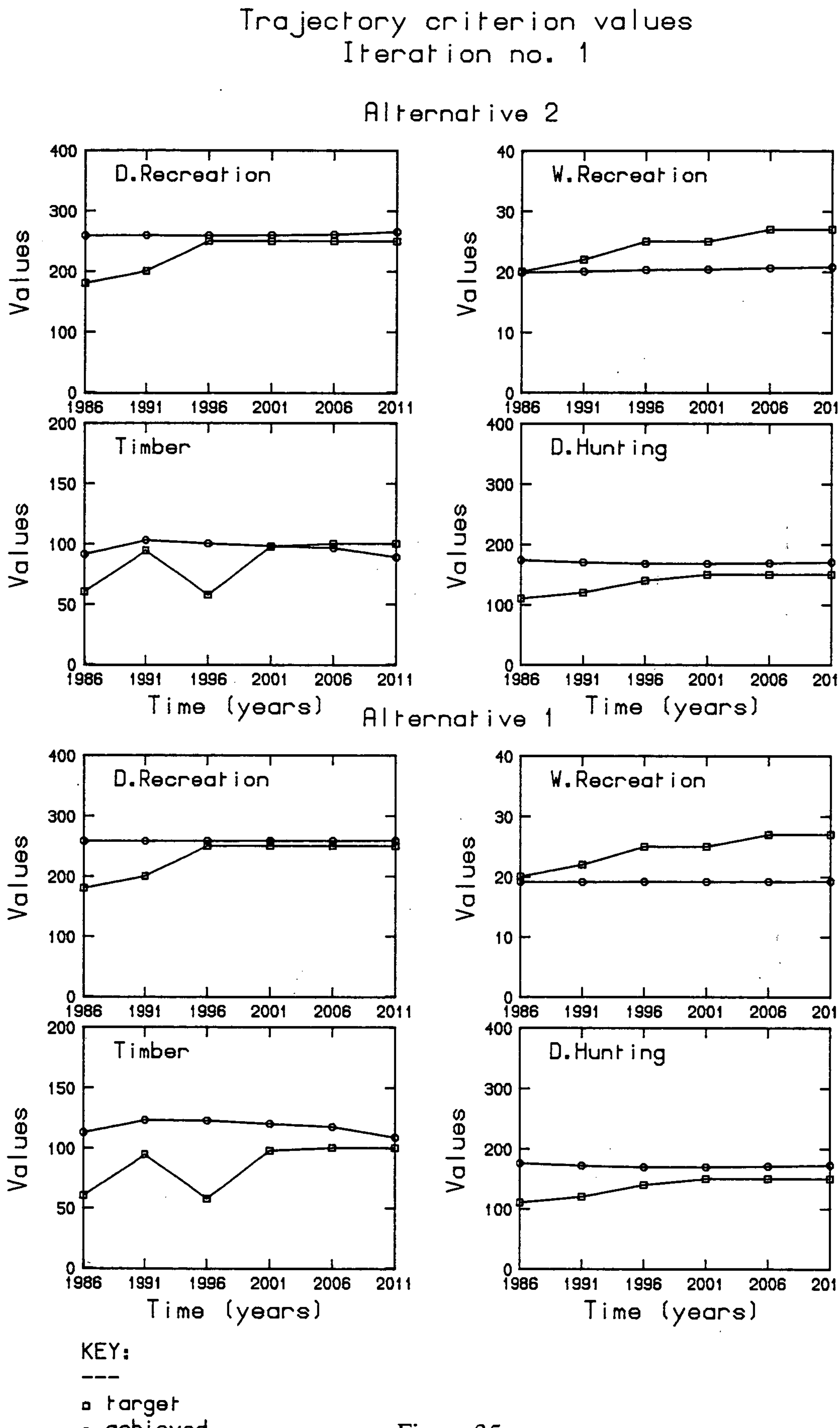

Criterion values
Iteration no. 1
2001
1996
Percentage
25.0
20.0
15.0
10.0
5.0
0.0
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 33



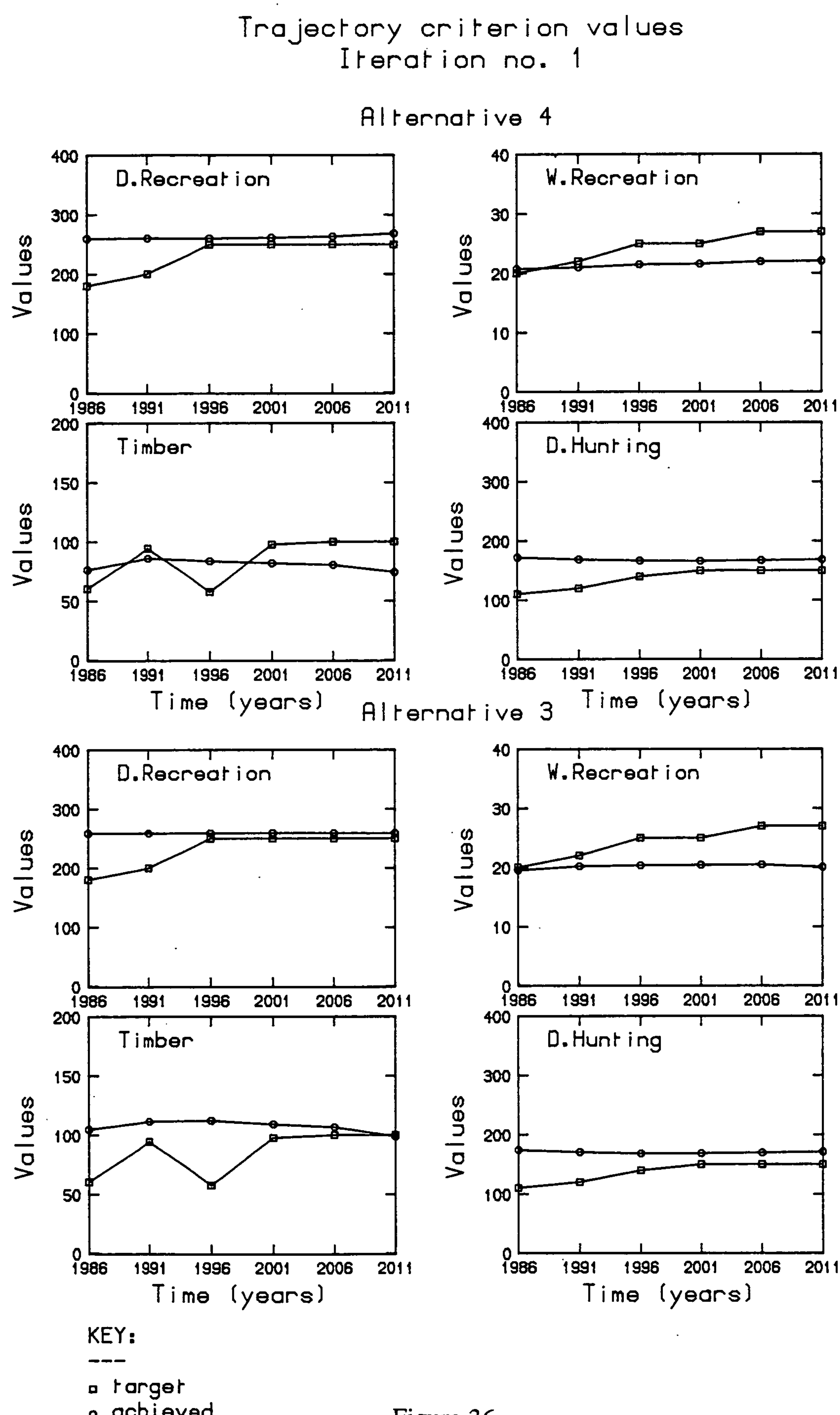
Criterion values
Iteration no. 1
2011
2006
Percentage
25.0
20.0
15.0
10.0
5.0
0.0
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 34



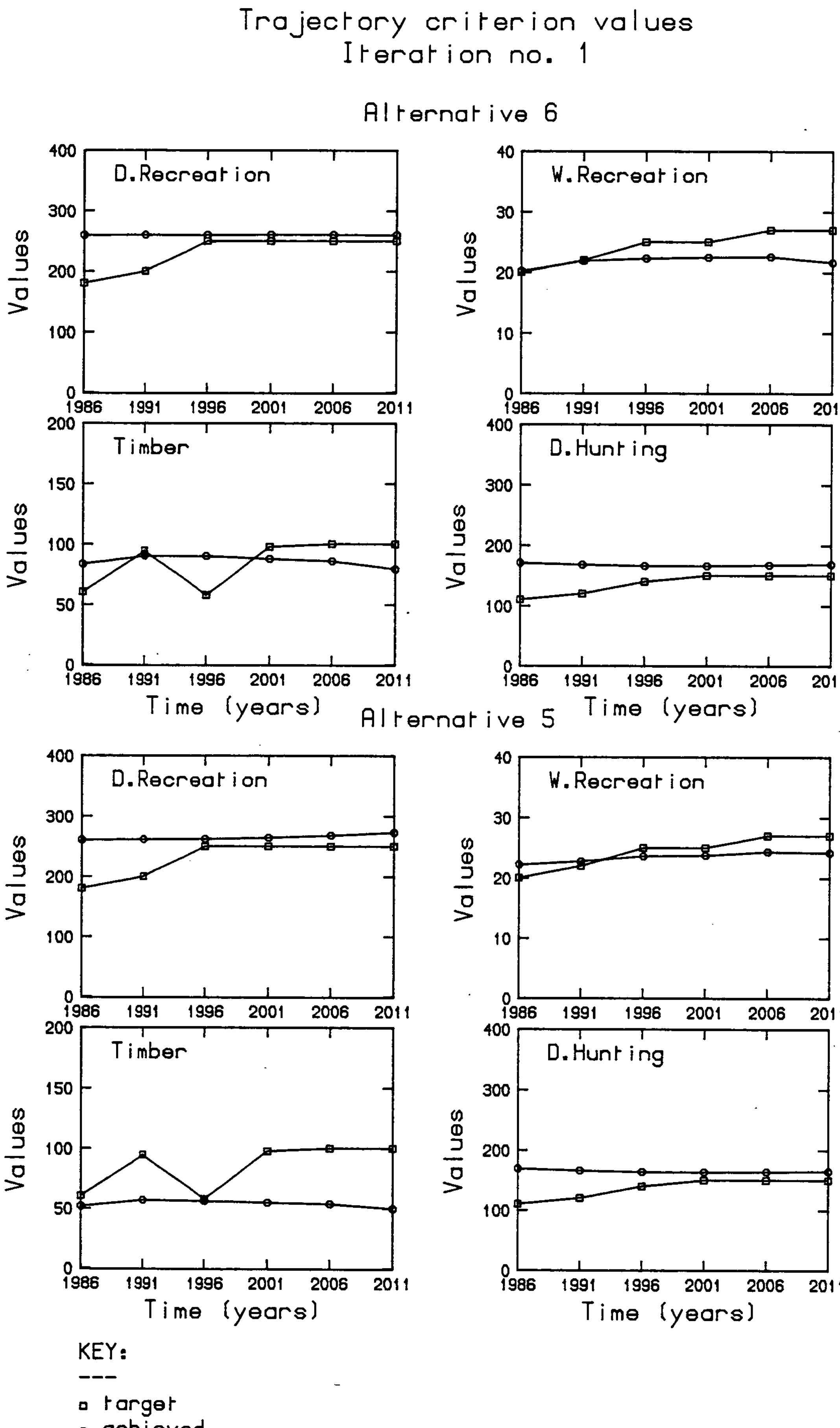
Trajectory criterion values
Iteration no. 1
Alternative 2
D.Recreation
W.Recreation
Timber
D.Hunting
Alternative 1
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
1986
1991
1996
2001
2006
2011
KEY:
---
target
achieved

Figure 35


Trajectory criterion values
Iteration no. 1
Alternative 4
D.Recreation
W.Recreation
Timber
D.Hunting
Alternative 3
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
1986 1991 1996 2001 2006 2011
0 100 200 300 400
0 10 20 30 40
0 50 100 150 200
KEY:

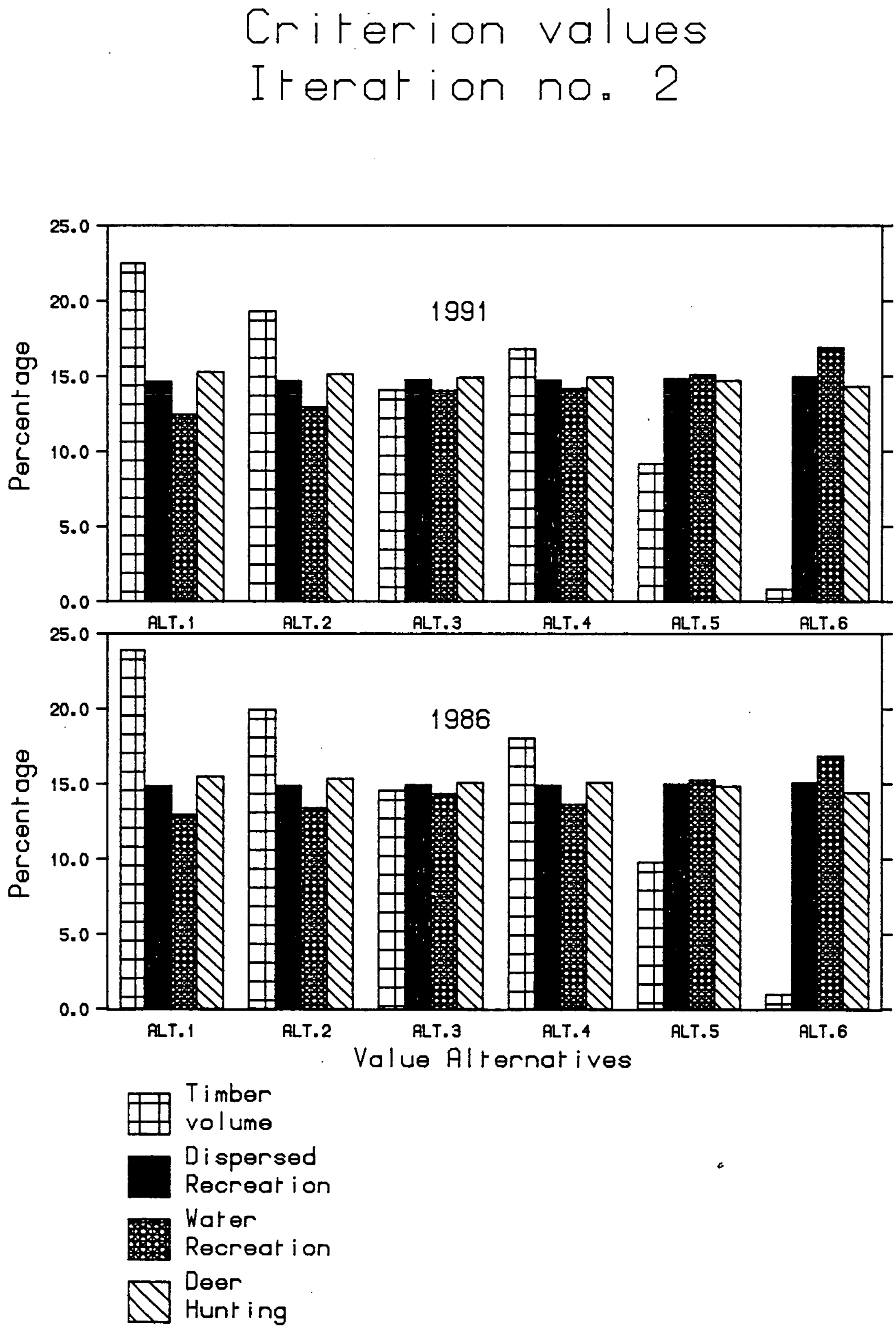
□ target
○ achieved

Figure 36



Trajectory criterion values
Iteration no. 1
Alternative 6
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
Alternative 5
D.Recreation
W.Recreation
Timber
D.Hunting
KEY:
target
achieved

Figure 37



Criterion values
Iteration no. 2
1991
1986
Percentage
25.0
20.0
15.0
10.0
5.0
0.0
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 38

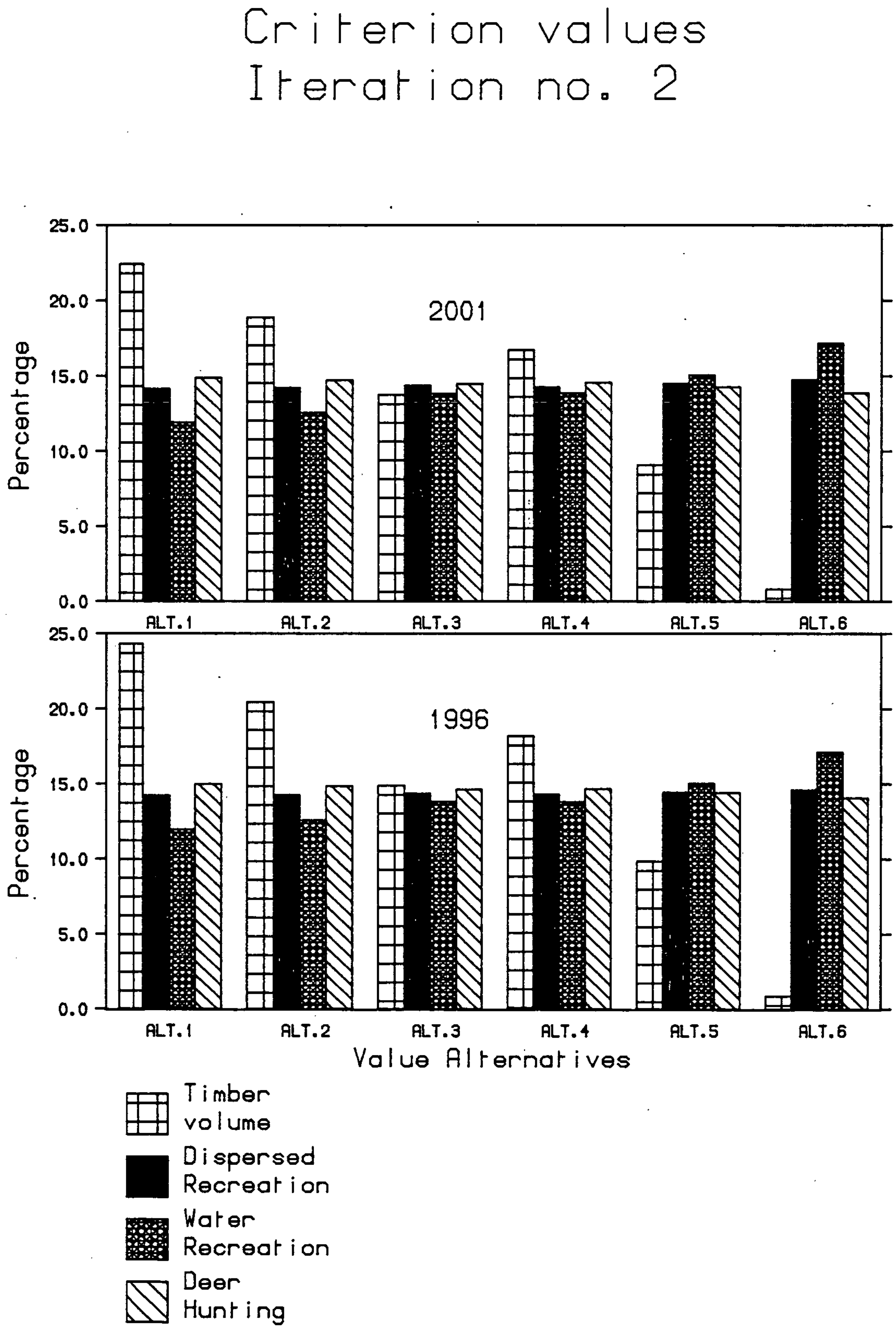

Criterion values
Iteration no. 2
2001
1996
Percentage
Value Alternatives
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
25.0
20.0
15.0
10.0
5.0
0.0
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 39

Criterion values
Iteration no. 2

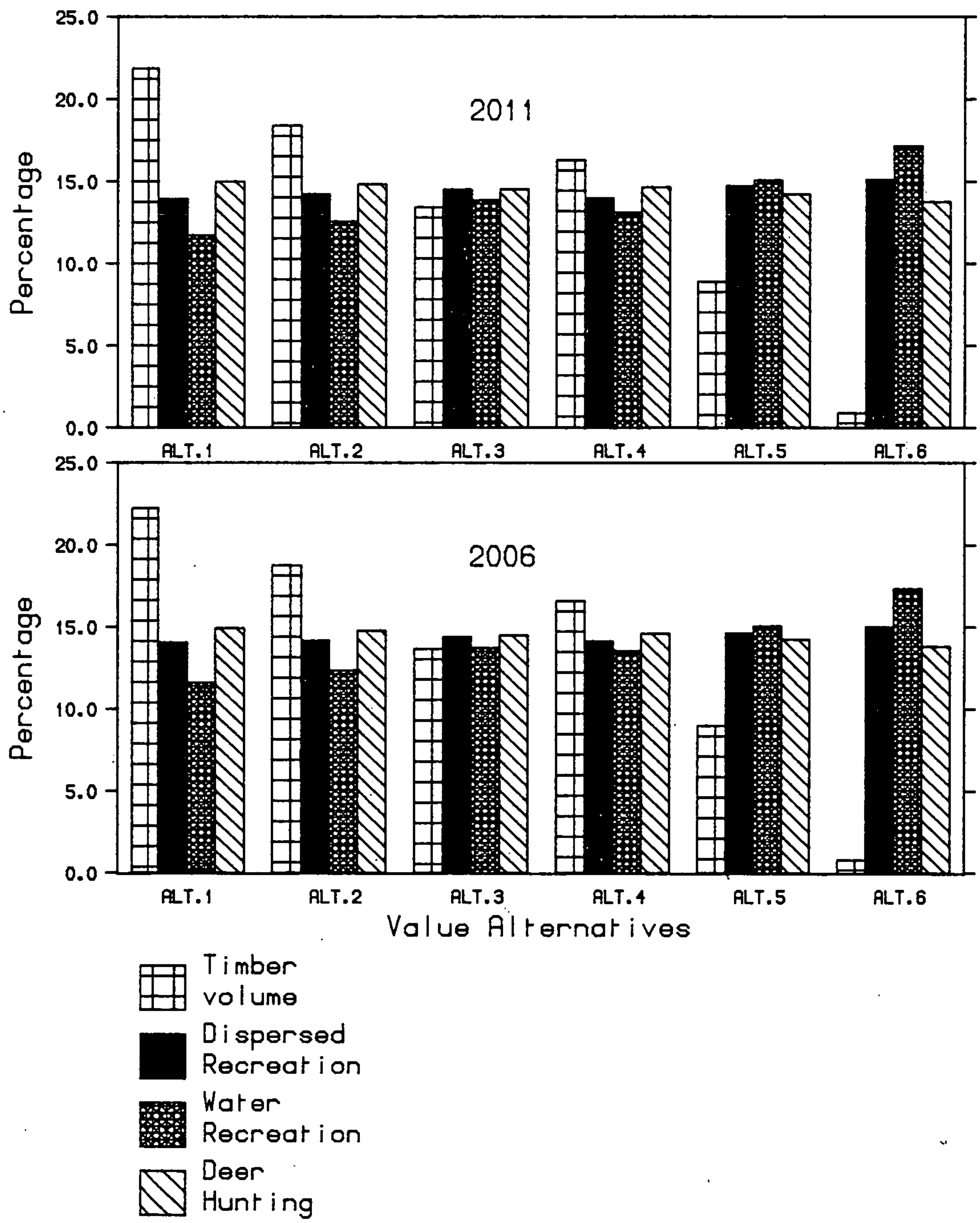
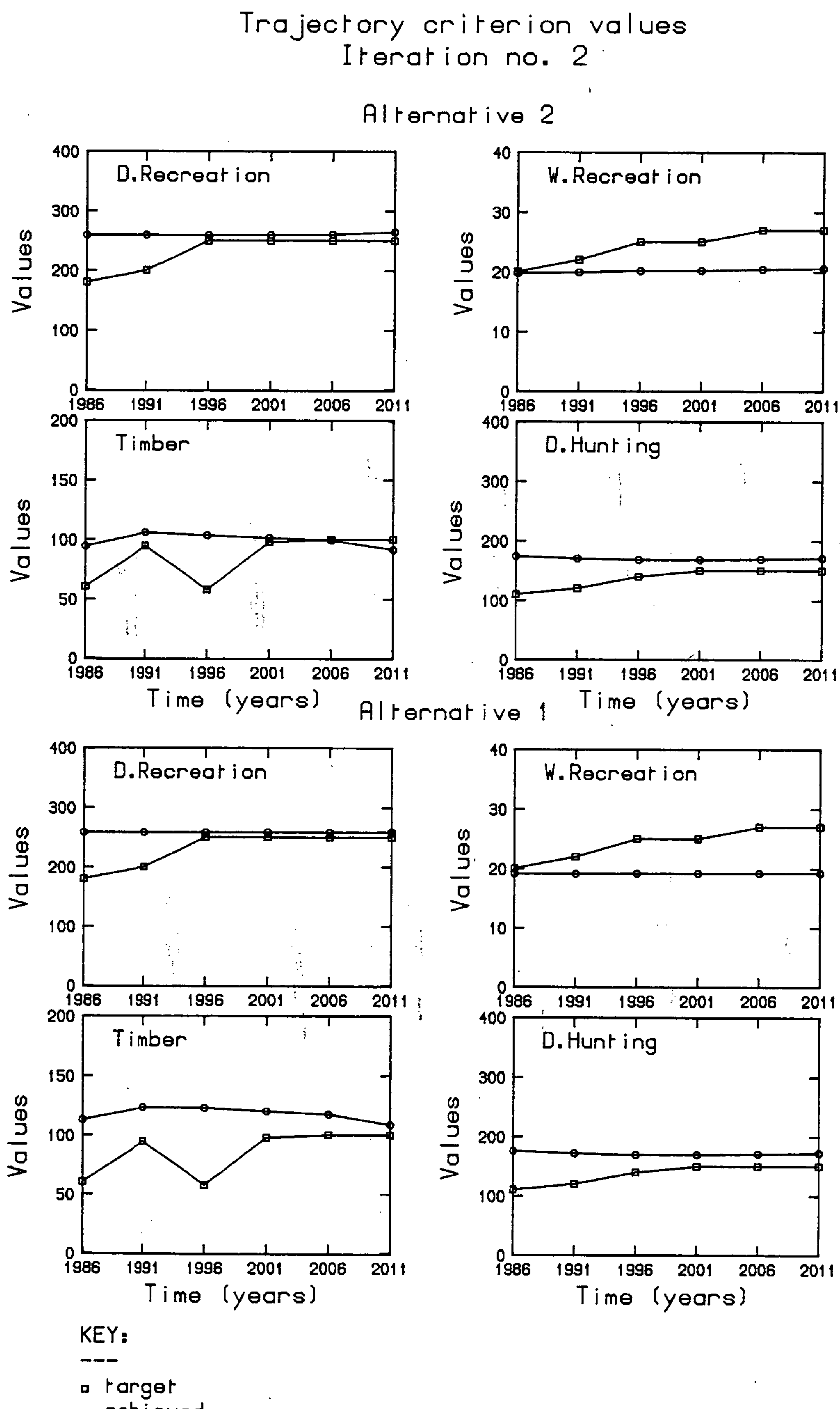
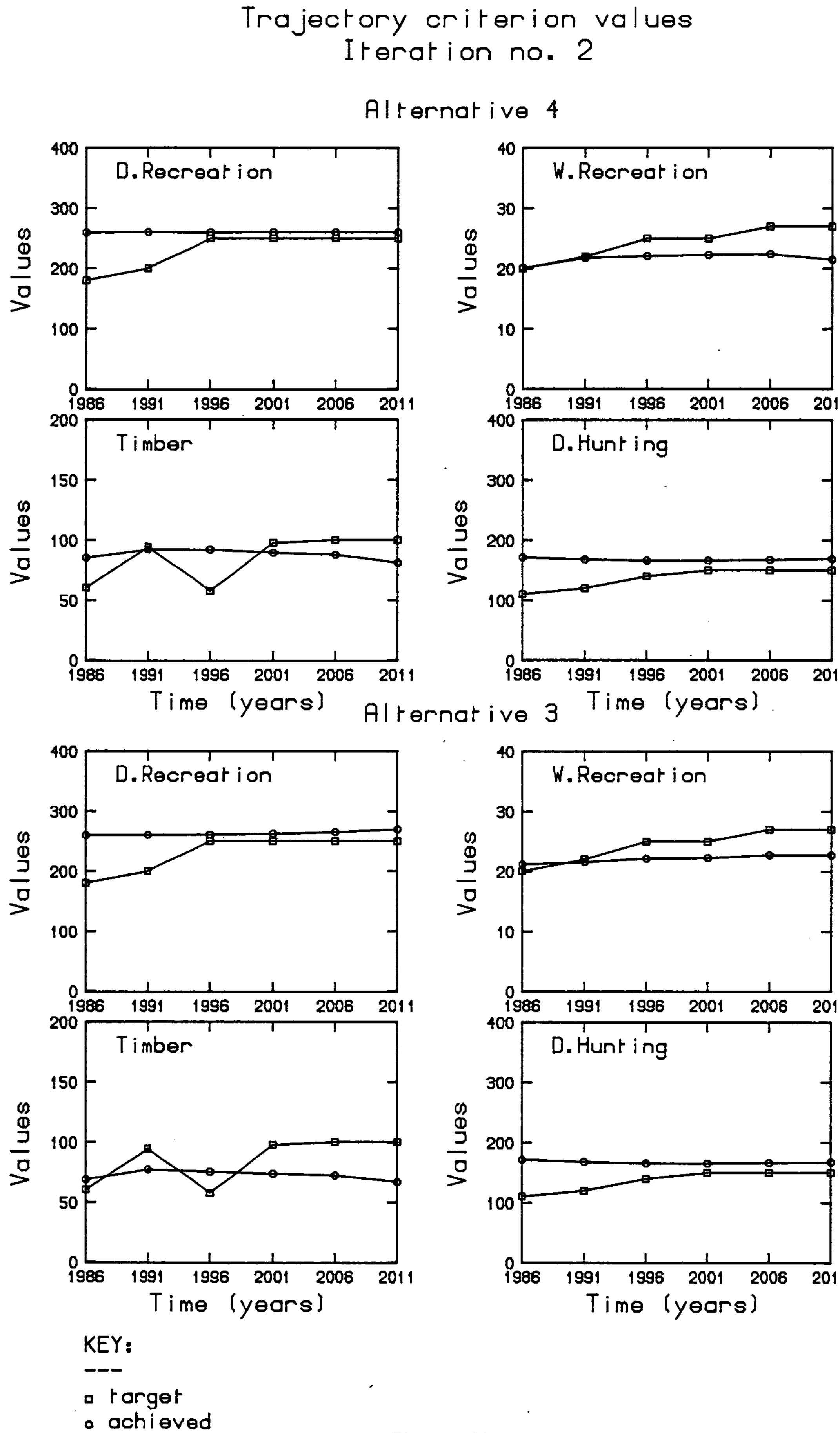


Figure 40


Trajectory criterion values
Iteration no. 2
Alternative 2
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
Alternative 1
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
1986
1991
1996
2001
2006
2011
KEY:

▫ target
∘ achieved

Figure 41


Trajectory criterion values
Iteration no. 2
Alternative 4
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
Alternative 3
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
1986
1991
1996
2001
2006
2011
KEY:

□ target
○ achieved

Figure 42

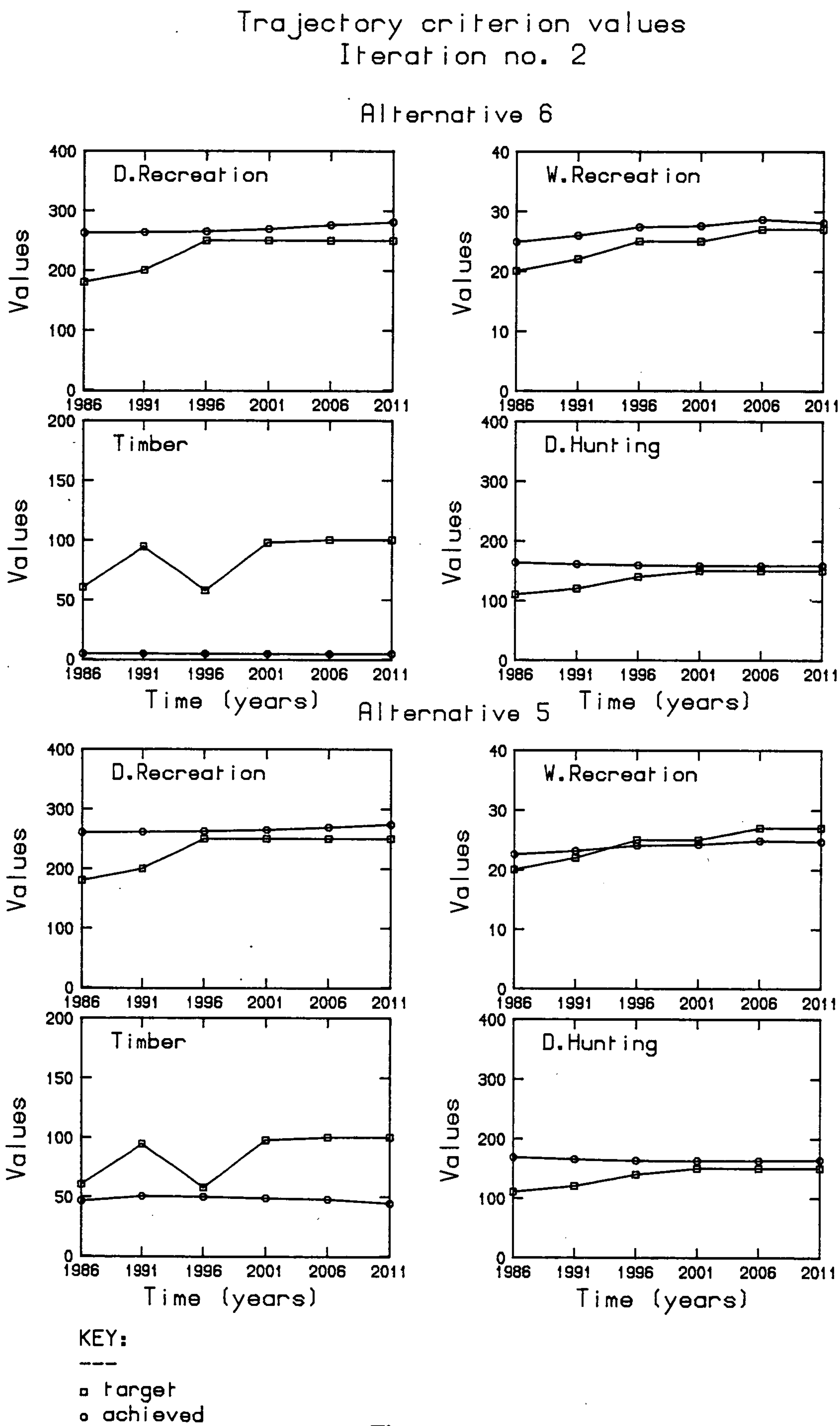
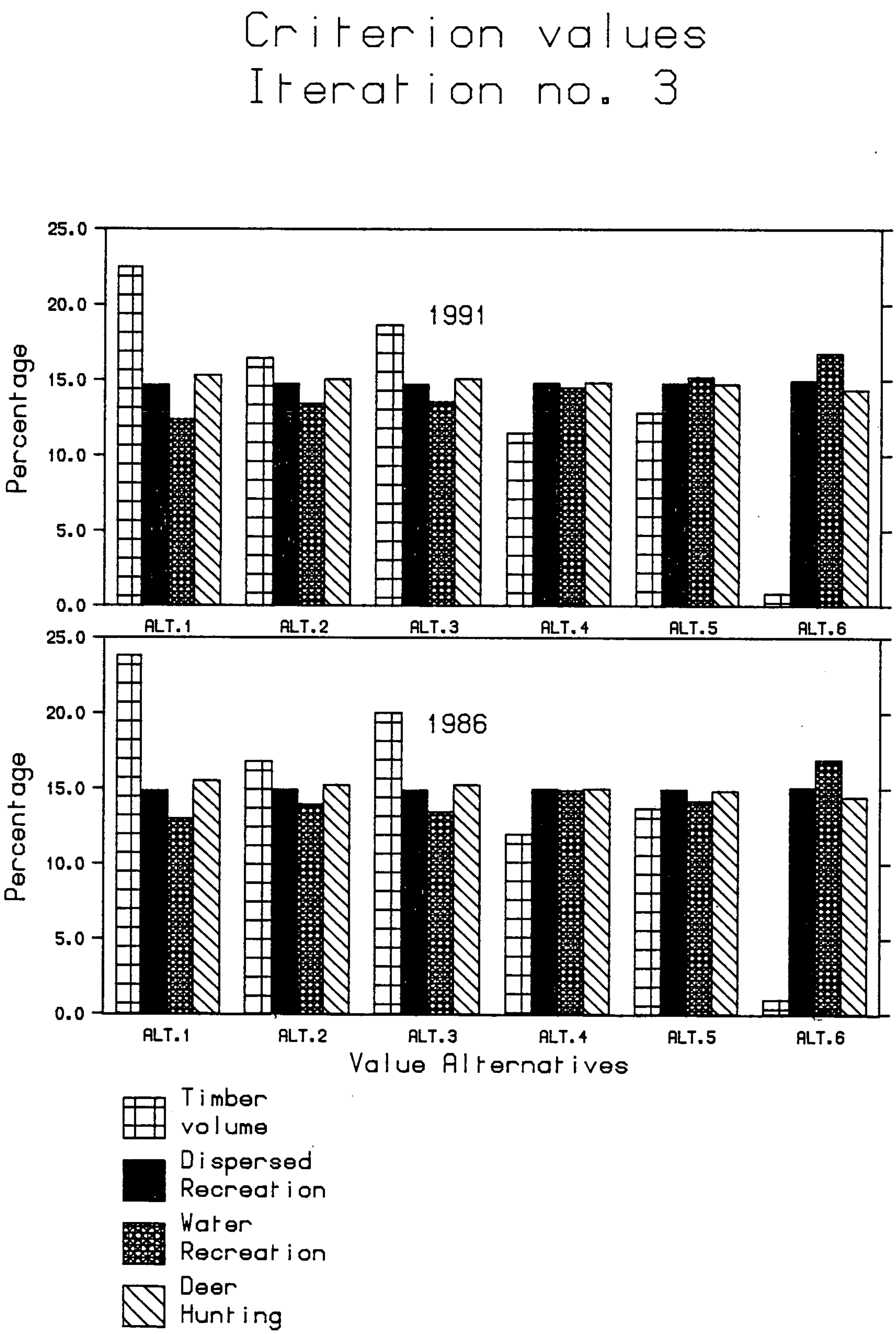

Trajectory criterion values
Iteration no. 2
Alternative 6
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
1986 1991 1996 2001 2006 2011
Alternative 5
D.Recreation
W.Recreation
Timber
D.Hunting
KEY:
target
achieved

Figure 43



Criterion values
Iteration no. 3
1991
1986
Percentage
25.0
20.0
15.0
10.0
5.0
0.0
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 44

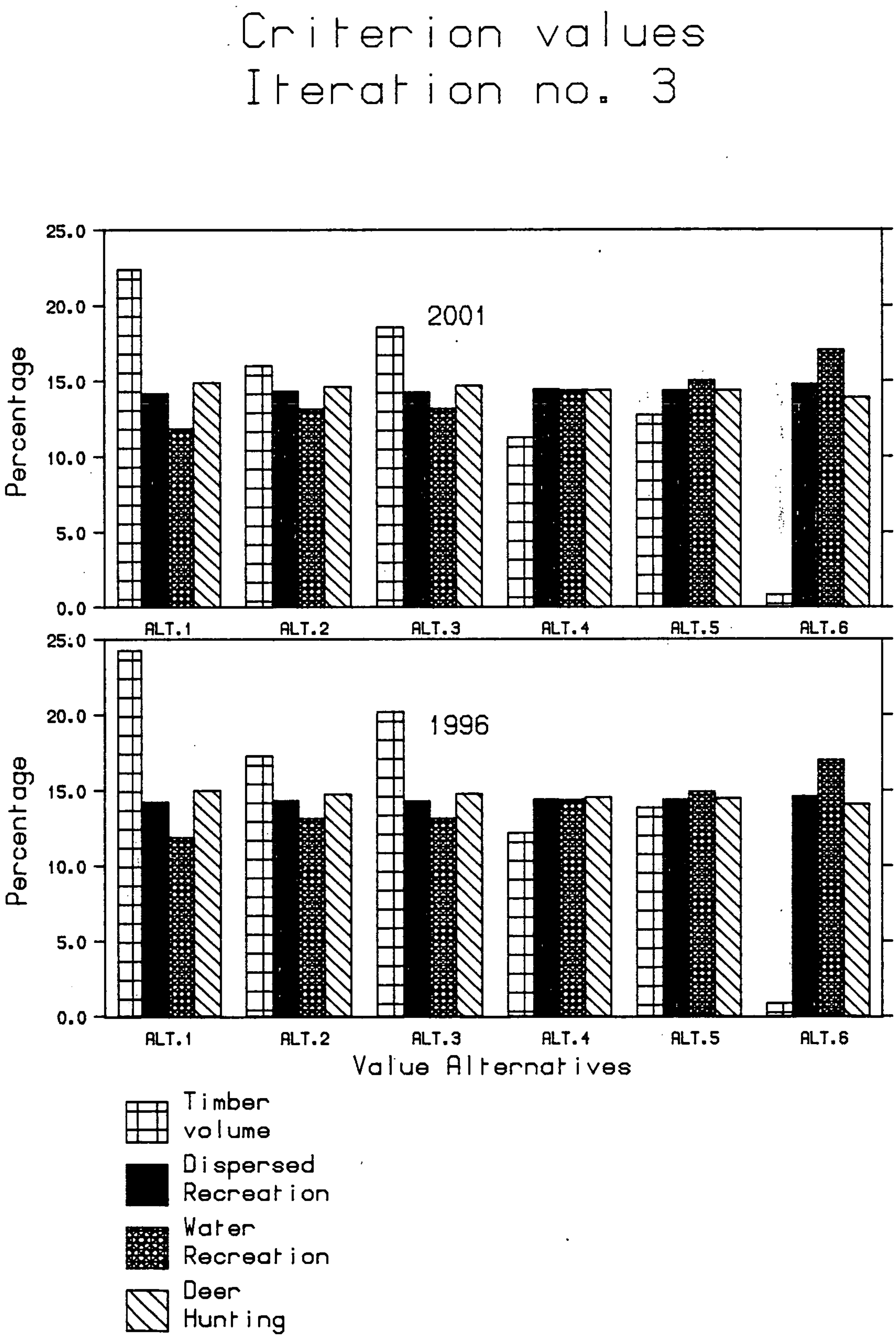
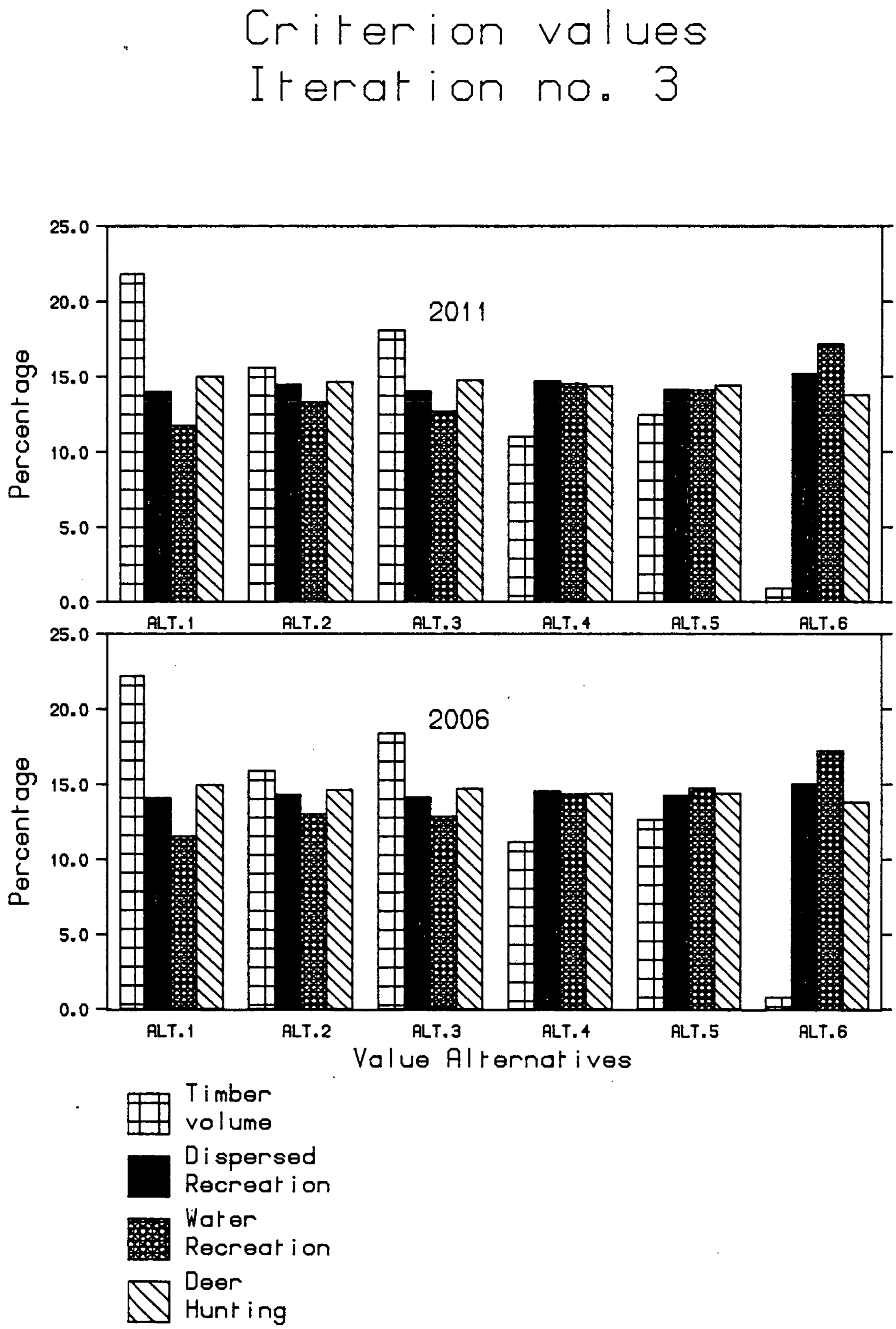
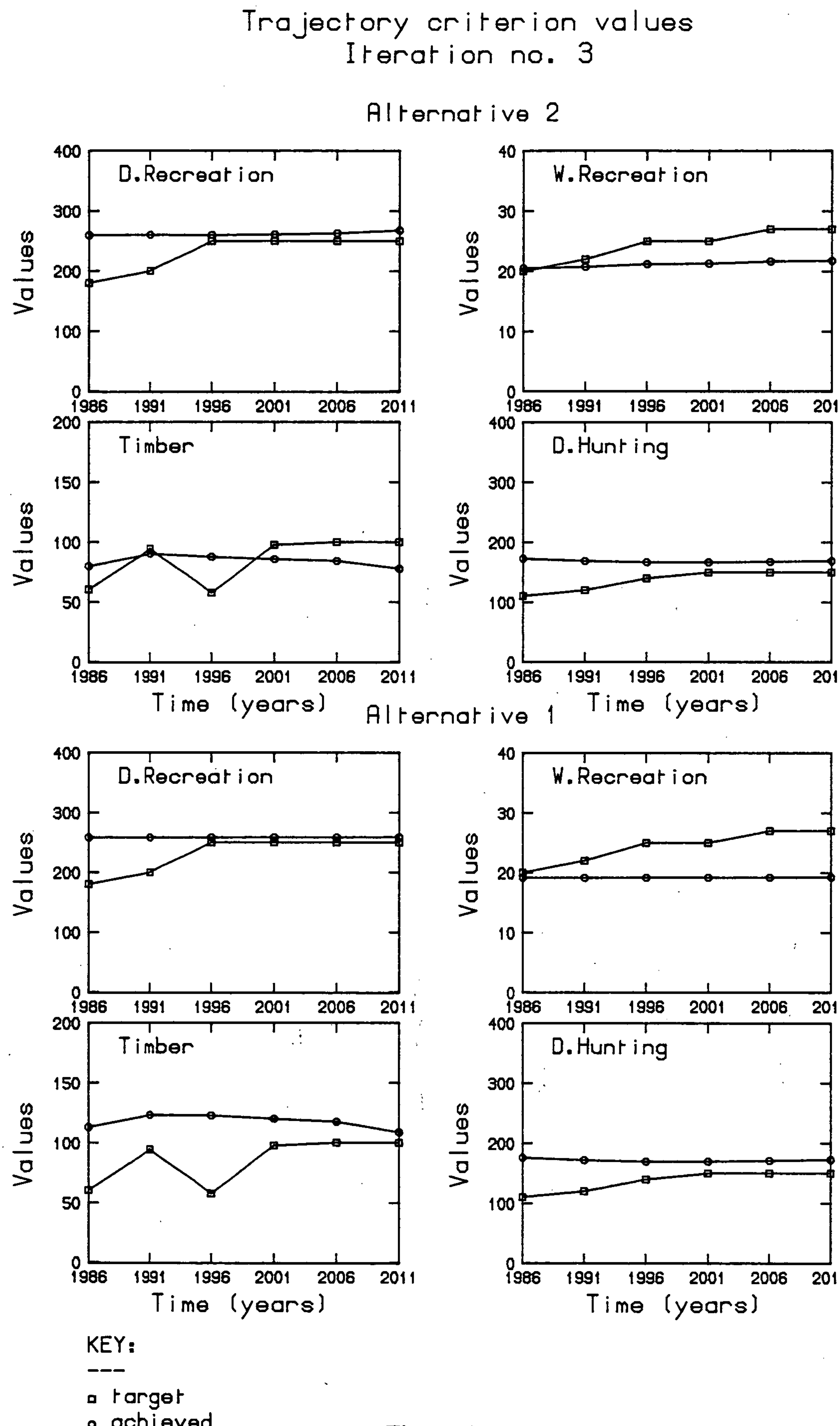

Criterion values
Iteration no. 3
2001
1996
Percentage
25.0
20.0
15.0
10.0
5.0
0.0
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 45



Criterion values
Iteration no. 3
2011
2006
Percentage
25.0
20.0
15.0
10.0
5.0
0.0
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 46



Trajectory criterion values
Iteration no. 3
Alternative 2
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
400
300
200
100
0
40
30
20
10
150
50
1986
1991
1996
2001
2006
2011
Alternative 1
KEY:
---
target
achieved

Figure 47

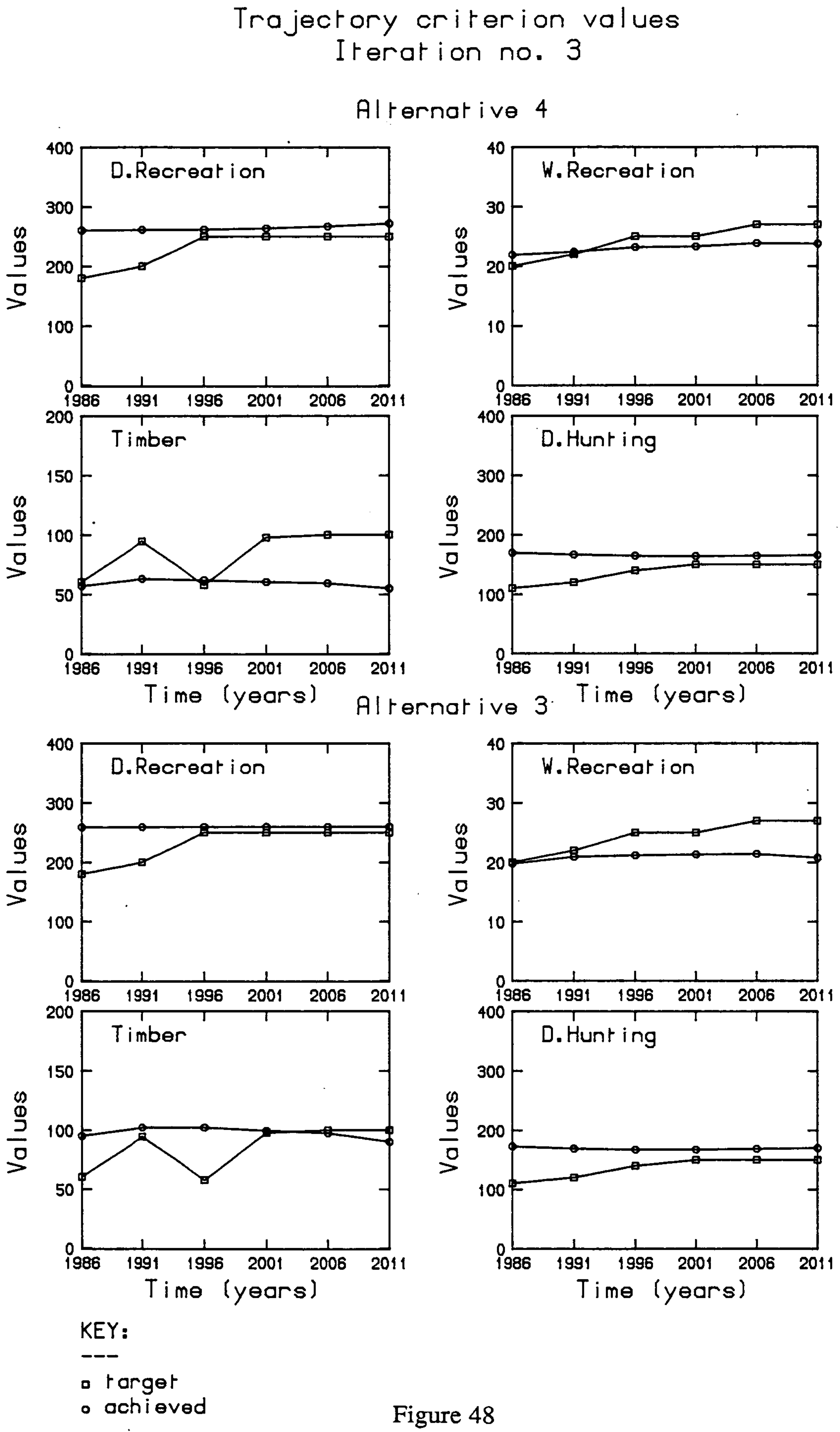

Trajectory criterion values
Iteration no. 3
Alternative 4
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
1986 1991 1996 2001 2006 2011
Alternative 3
D.Recreation
W.Recreation
Timber
D.Hunting
KEY:
---
target
achieved

Figure 48

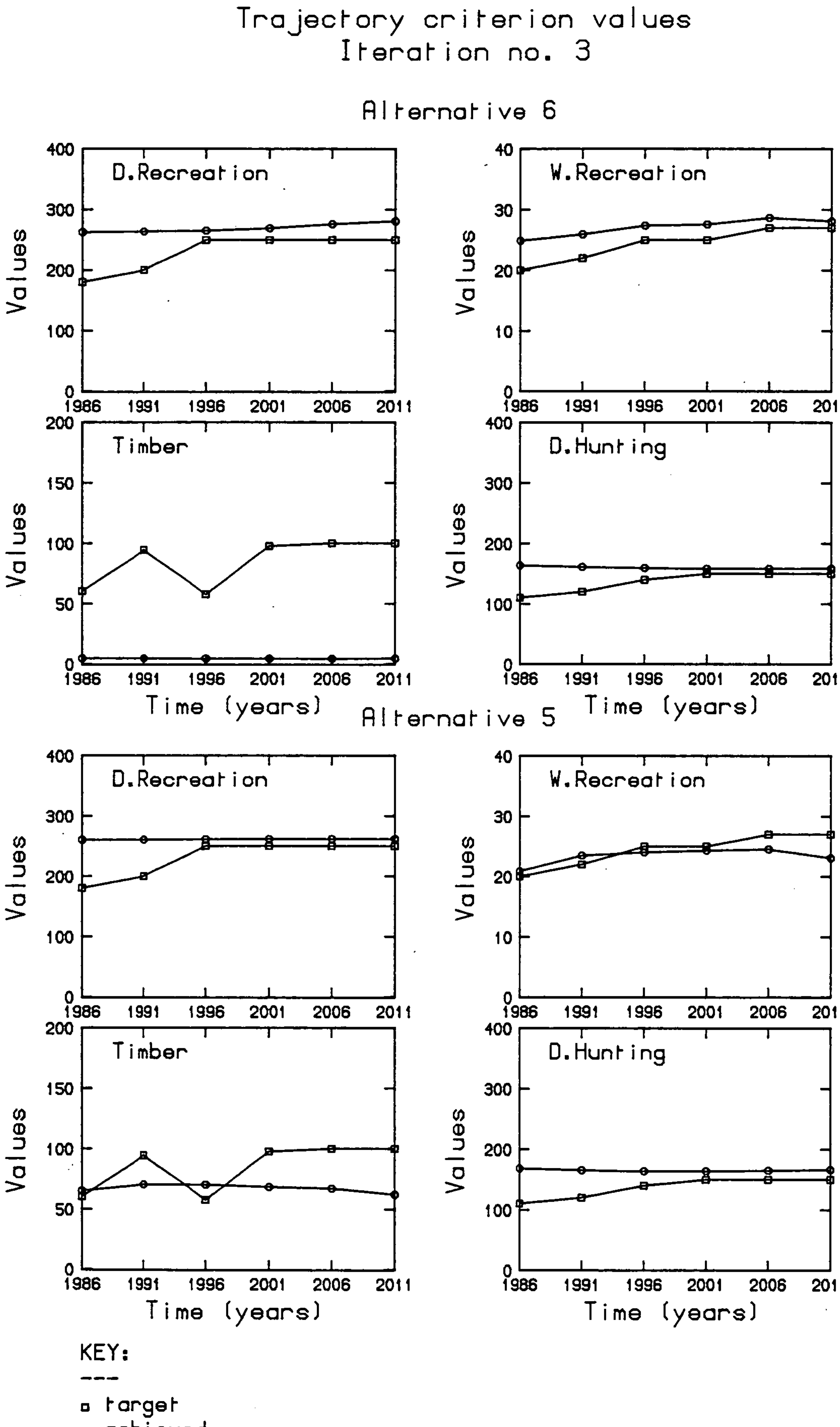

Trajectory criterion values
Iteration no. 3
Alternative 6
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
Alternative 5
D.Recreation
W.Recreation
Timber
D.Hunting
KEY:
target
achieved

Figure 49

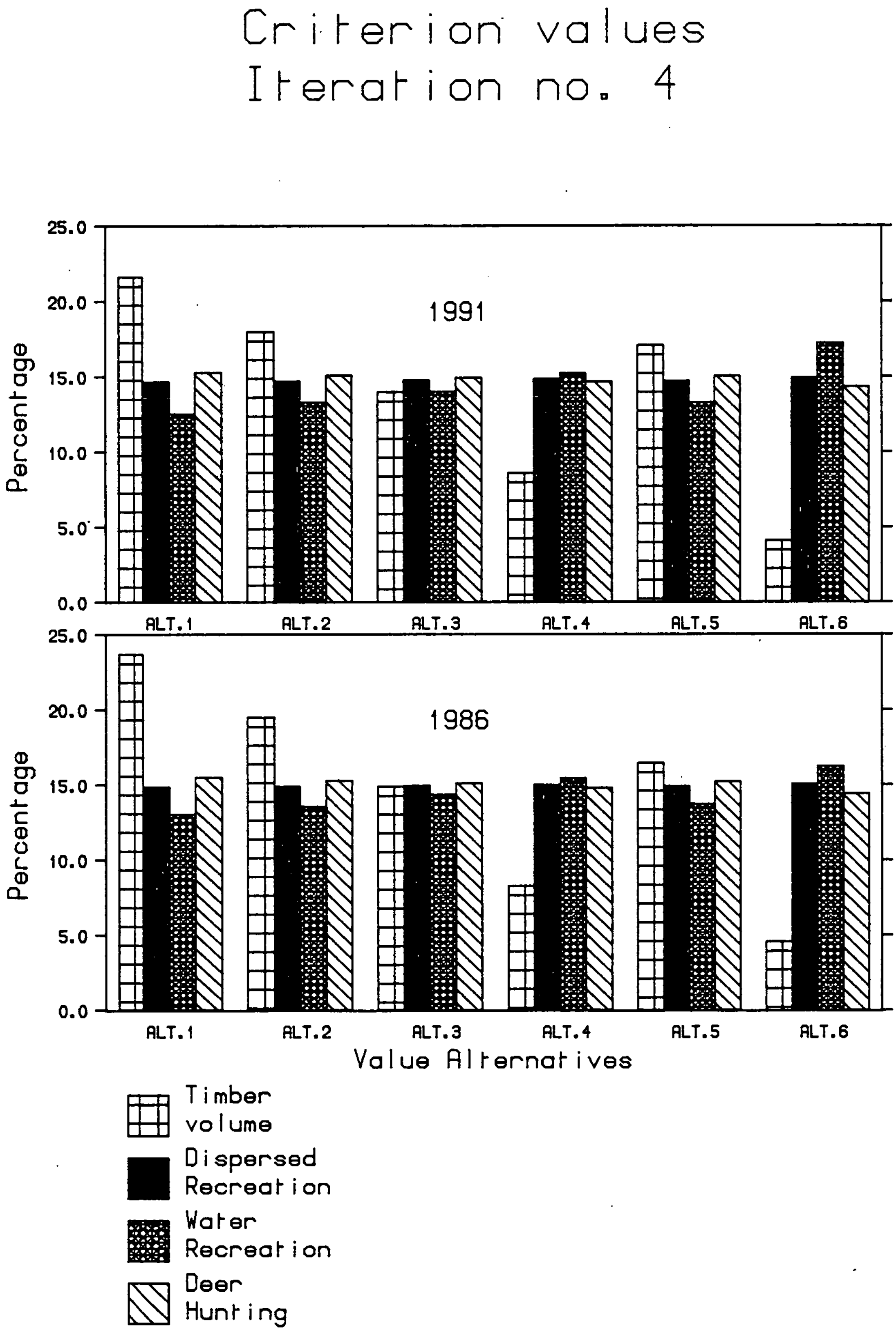

Criterion values
Iteration no. 4
25.0
20.0
15.0
10.0
5.0
0.0
Percentage
1991
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
1986
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 50

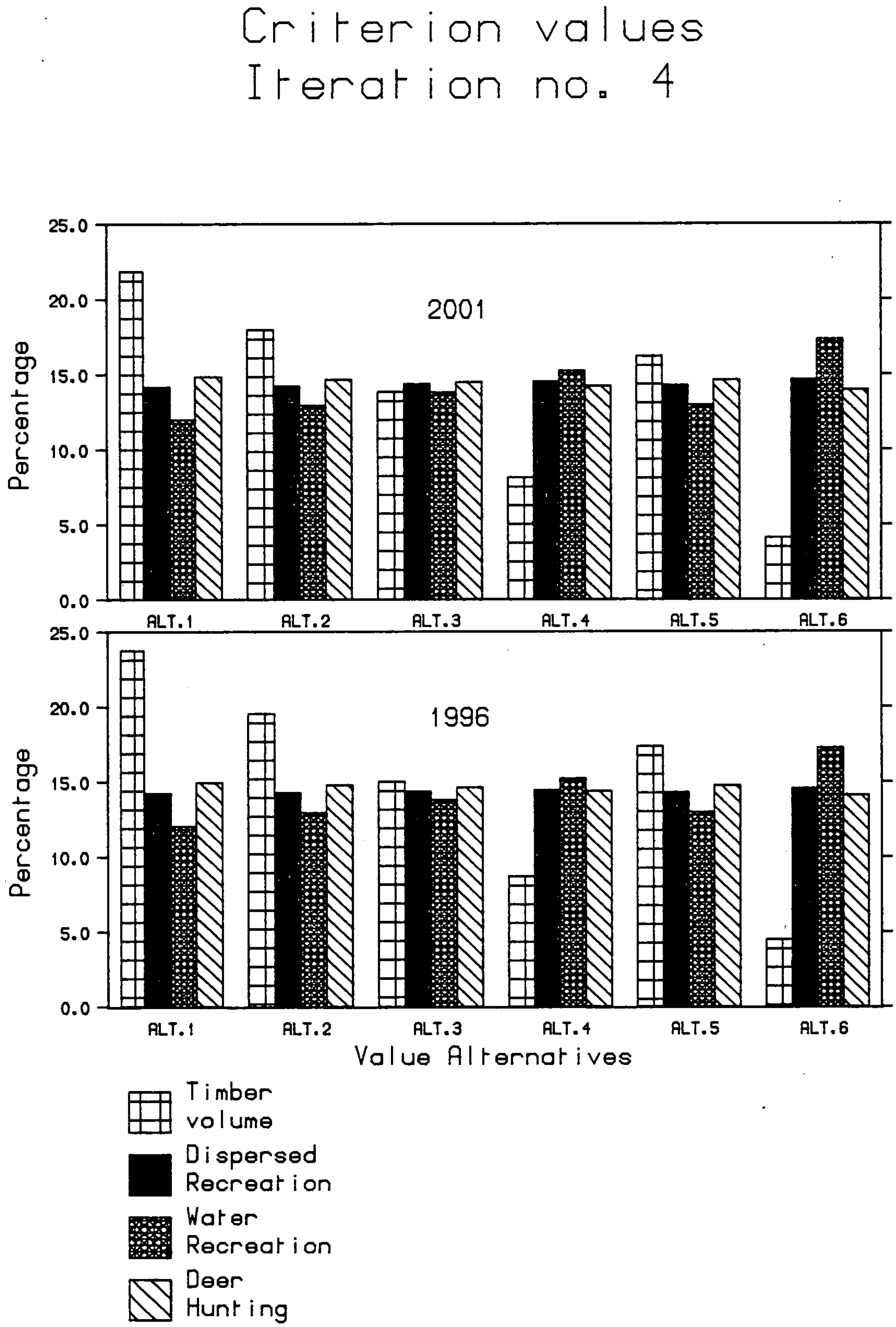

Criterion values
Iteration no. 4
25.0
20.0
15.0
10.0
5.0
0.0
Percentage
2001
ALT.1
ALT.2
ALT.3
ALT.4
ALT.5
ALT.6
1996
Value Alternatives
Timber volume
Dispersed Recreation
Water Recreation
Deer Hunting

Figure 51

Criterion values
Iteration no. 4

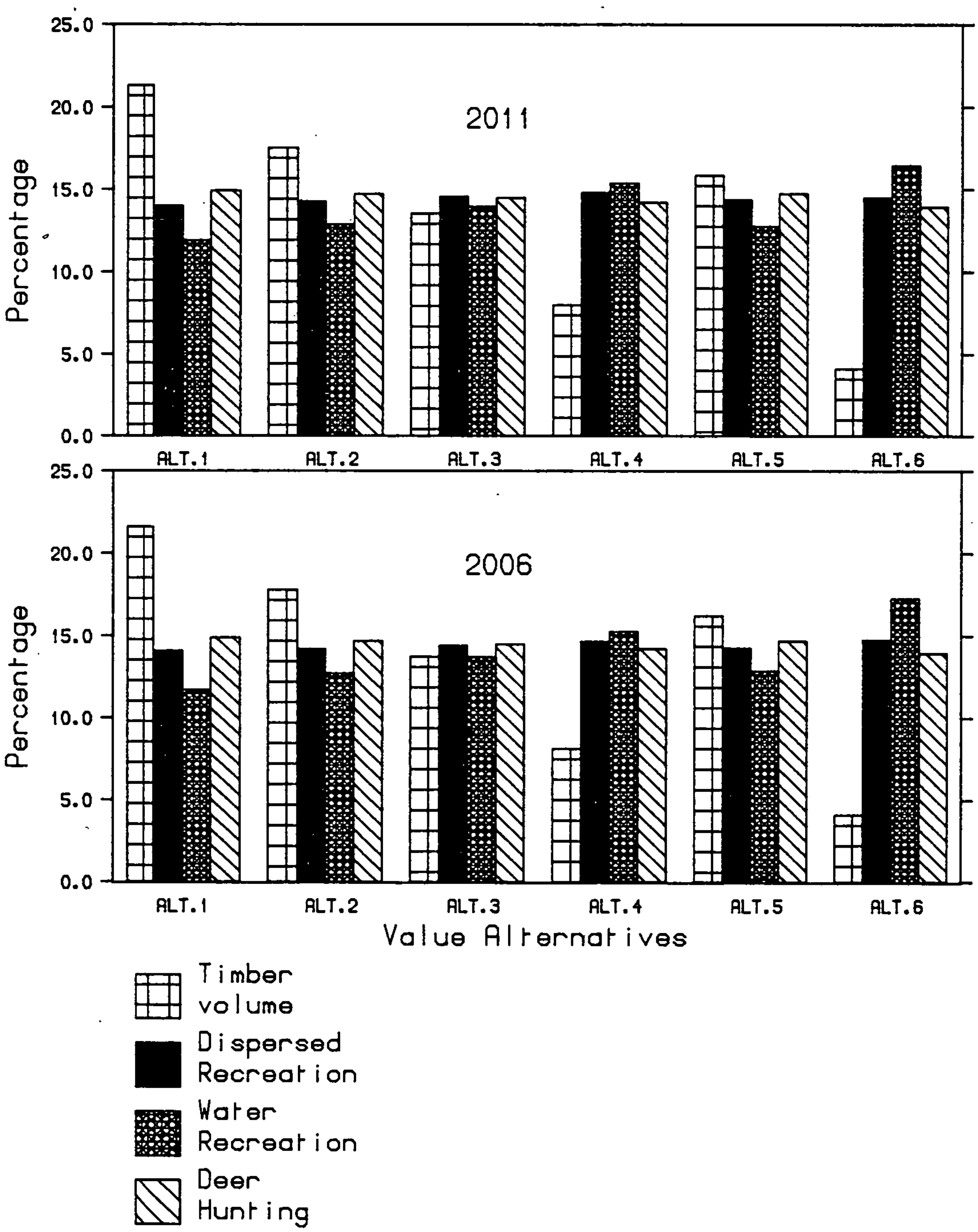


Figure 52

Trajectory criterion values
Iteration no. 4

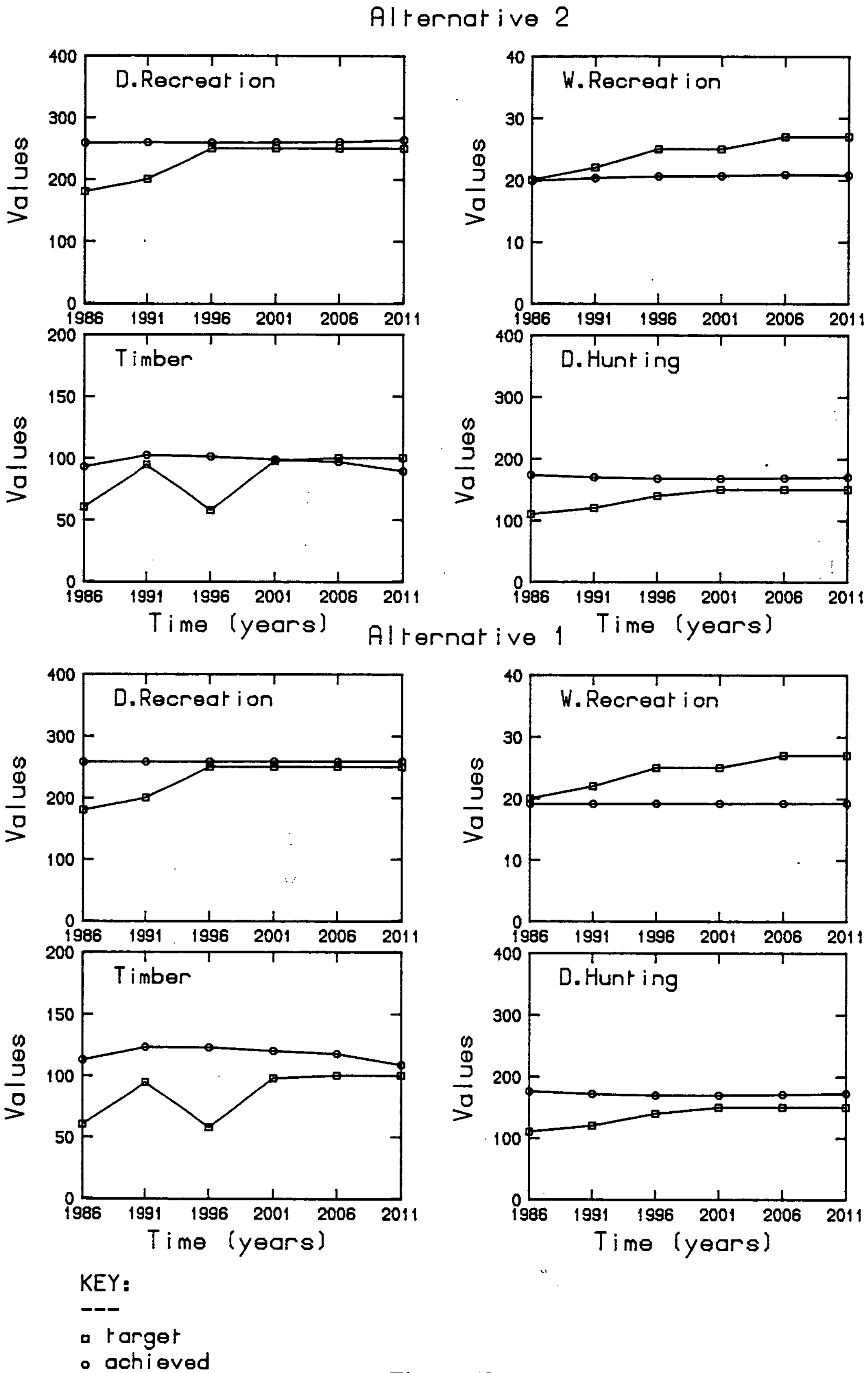
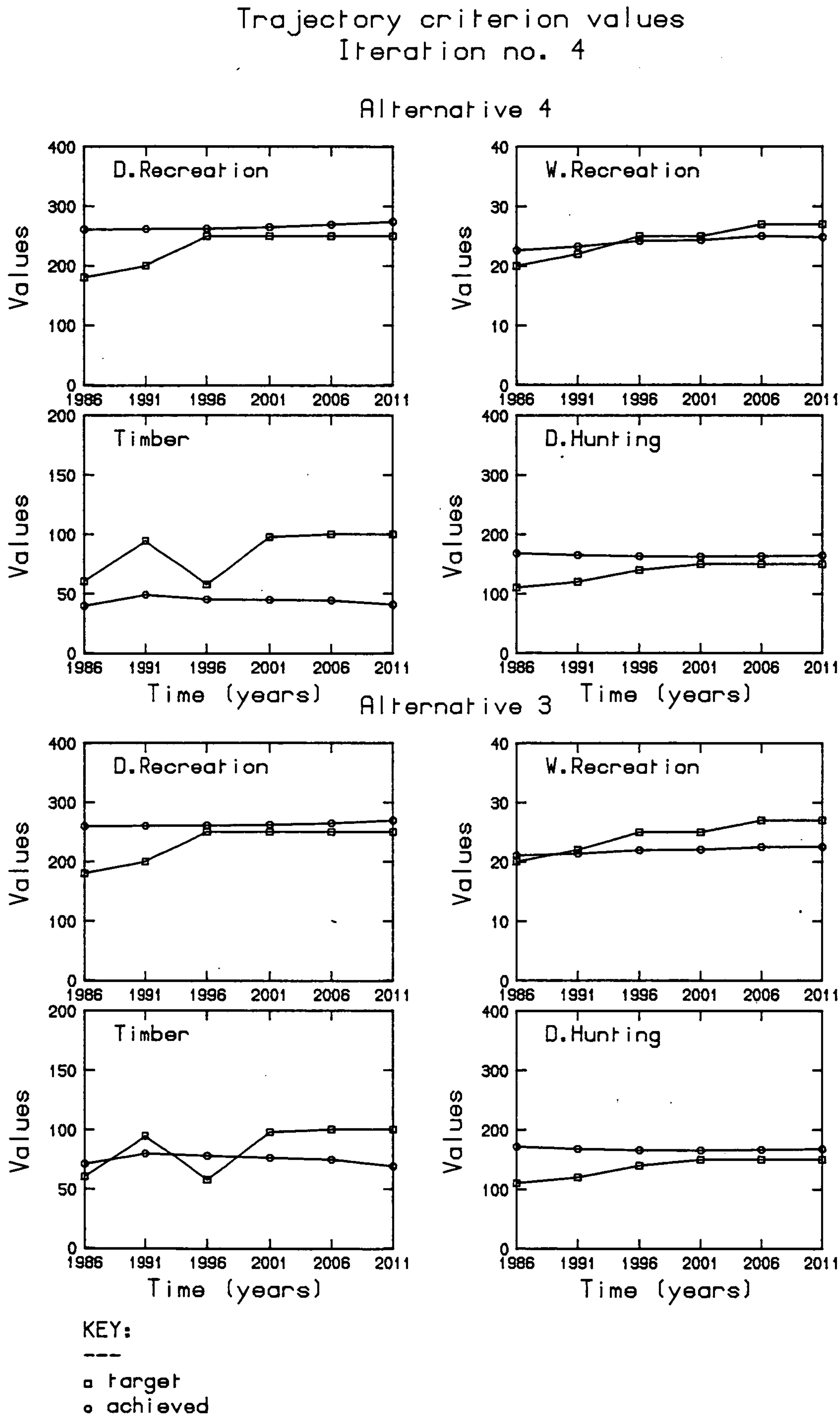
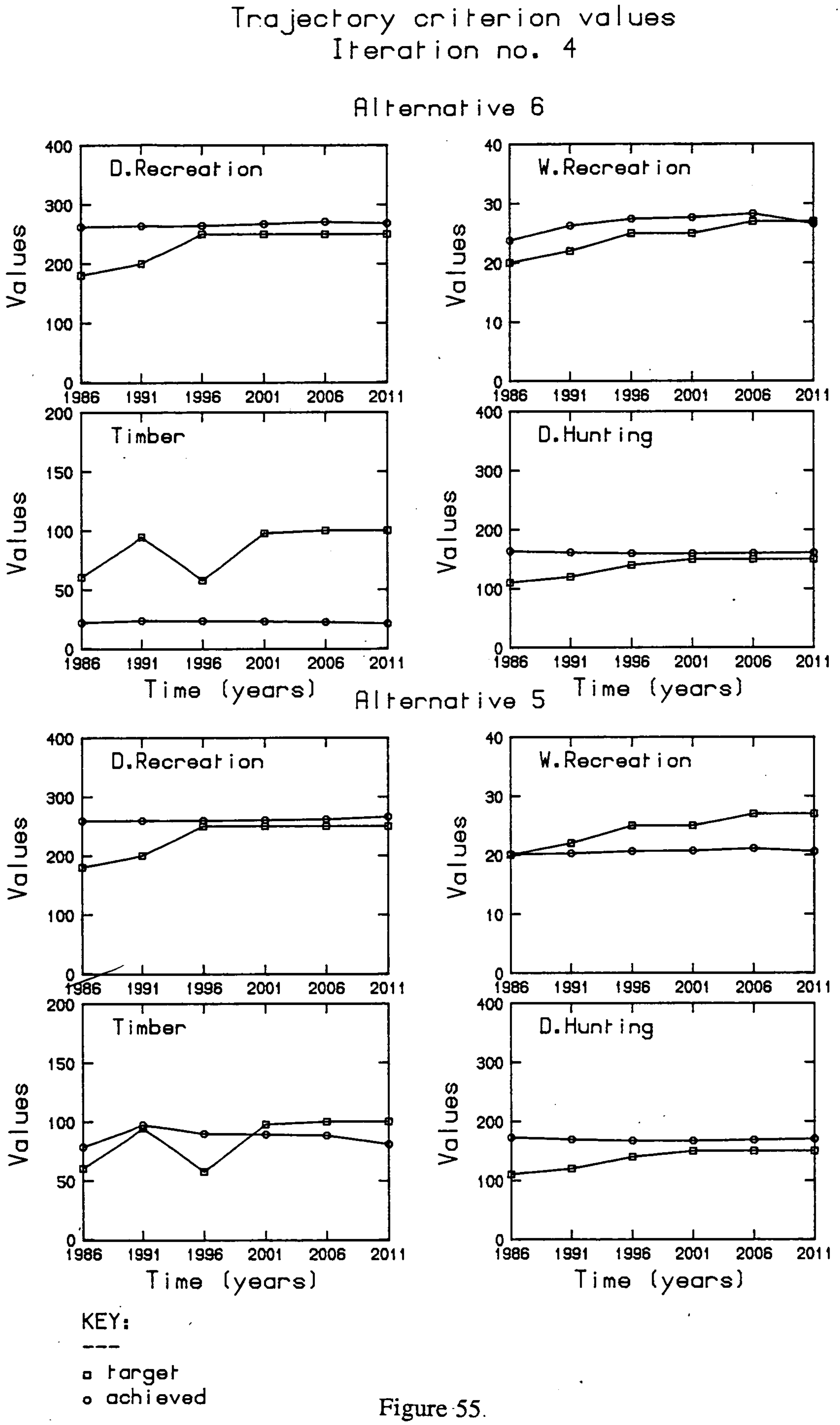


Figure 53



Trajectory criterion values
Iteration no. 4
Alternative 4
D.Recreation
W.Recreation
Timber
D.Hunting
Alternative 3
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
1986
1991
1996
2001
2006
2011
KEY:
target
achieved

Figure 54


Trajectory criterion values
Iteration no. 4
Alternative 6
D.Recreation
W.Recreation
Timber
D.Hunting
Alternative 5
D.Recreation
W.Recreation
Timber
D.Hunting
Values
Time (years)
KEY:

□ target
○ achieved

Figure 55.

CHAPTER NINE. CONCLUSIONS

9.1 CONCLUSIONS

There are two types of conclusions which can be drawn from this work. The first type relates to the forest management results, while the second type to the suitability of the FORM DSS as a tool for decision-making at the forest district level.

The final solution (alternative 5, iteration 4) showed that the dispersed recreation and deer stalking goals can be met throughout the specified planning horizon. Indeed, there is scope for their levels to be increased.

The timber production goal can be met until year 2001, but it is underachieved during the remaining years of the planning horizon. This suggests that the corresponding target values have to be lowered or the budget and nature conservation levels to be altered. The first option seems a more realistic proposal as the target values of the last two 5-year planning periods are rather high in relation to the productive potential of the forest under the management regimes used in this investigation.

The water-based recreation goal, with the exception of year 1986, is underachieved throughout the specified planning period. This also implies that the target values should be lowered. This does not appear to be a problem, as recreation input values have been based on the statistical response models, which have been presented in chapter 2. These refer to the recreational potential of the forest, rather than actual recreational use. Therefore, the achieved values for both dispersed and water-based recreation reflect potential recreational development of the Queen Elizabeth Forest Park.

The sensitivity analysis showed that no intensive management is required to implement this optimal solution. Indeed, considering the management regimes under investigation, more land can be granted to conservation and still be close to the specified goal targets. However, these management regimes do not represent all the feasible regimes for the forest. The main reason for not including in FORM a larger number of alternative regimes was the lack of appropriate data which was not possible to be collected during the time of this project.

The FORM DSS is a flexible forest system model, which can serve as a decision-making tool for multi-objective forest tactical management and planning at the forest district level. Some of its features make it superior to other approaches, such as goal programming, which have been used to a greater extent to solve various types of forest management problems. These features can be summarized as follows:

1) The weighting procedure is done internally by the algorithm and the forest manager does not have to preempt any priorities before the solution process starts, as it is required by goal programming models.

2) The L_∞ -norm, which was used to sample the efficient set, can generate points which are not extreme points of the feasible solution set, in contrast to L_1-norm used in goal programming which converges only to extreme points.

3) A group of solutions is presented at each iteration to the forest manager, who is thus given more flexibility in changing goal targets as more information is gained about the problem. Goal programming can only generate one solution at a time. However, for multi-period models, such as the Queen Elizabeth case study model, this feature can turn out to be a disadvantage, as a substantial number of criterion values is generated which may confuse the forest manager. It is believed that the graphics facility has alleviated this problem and there is scope for more to be done in this area.

4) Finally the user is not assumed mathematically sophisticated. Menus, tables and graphs have been designed, so that they could be meaningful in the forestry context.

However, as with all models more can be done so that better performance of the system can be achieved and the forest manager could develop more confidence to solutions offered by the system. In the next section, some of the areas for future research regarding further development of FORM are presented.

9.2 FURTHER EXTENTIONS TO THE FORM DSS

Models are only a representation of the real world. This implies that situations are represented on the basis of assumptions and therefore are subject to improvements. The DSS presented in this thesis is not an exception. In this section, some areas in the build up of the system, which require further research are pointed out.

In Phase 1, the habitat modelling of the forest has the basic structure of a geographic information system (GIS). Generally, the processing functions of these systems can be grouped in four categories (Berry, 1987):

a) Computer mapping

b) Spatial data base management

c) Spatial statistics

d) Cartographic modelling.

Since incorporation of spatial habitat modelling in the FORM DSS is inventory-oriented, a structure for the a) and b) categories only has been developed. However, structures for the c) and d) groups can also be integrated to better extend the analytical processes of the system. Recent research (mainly after 1986) brought in the market very elaborated hardware and software. This technology can be interfaced in the system, so that spatial information would be manipulated and processed more accurately. Even more an expert system can be developed to deal more efficiently with spatial forest data base management.

Phase 2 includes response models for timber production, dispersed recreation, water-based recreation and deer stalking. This by no means suggests that these products and services are the only ones to be considered in forest management. FORM_CFGENS can be extended to include also scenic beauty models, which are clearly different from recreation models, since there is a distinct difference between visual amenity and physical resources for recreation. Although a considerable amount of work on scenic beauty models has been carried out in North America (Hull IV and Buhyoff, 1986; Schroeder and Daniel, 1981; Arthur, 1977; Buhyoff, Wellman and Daniel, 1982; Brown, 1987; Buhyoff, et al., 1986) none of this type was found in this country. Time constraints regarding completion of this project did not allow development of a scenic beauty model. Therefore, visual amenity is not considered in the present development stage of FORM.

Also by including only red deer stalking in the model, is not suggested that other game species are not as valuable as deer. Roe deer was excluded, because adequate data information was not available. There is a strong need for development of habitat models for systems, such as FORM to give more accurate results. The structure of FORM allows for incorporation of any new information of this type and it is believed this is a desirable feature of the system.

In phase 4, that is the optimization phase, only investigation of the MINIMAX approach was attempted. Some reasons for not using goal programming, which has been the most popular approach so far, were presented in the previous section. However, there are several Operations Research methods (see chapter 4) which can be potential candidates for investigation as regards their application to multi-objective forest management problems.

FORM runs on EMAS (Edinburgh Multi-Access System) IBM 370-XA mainframe computer and this may be viewed as a disadvantage of the modelled system. Storage requirements (the Queen Elizabeth Forest Park subcompartment data base included 5,000 subcompartments with 16 variables each) did not allow investigation on micro-computers. The British Forestry Commission, however, affords a mainframe computer system and running the model would present no particular problems. A further development of FORM can be attempted on micro-computers.

Finally the model remains to be tested with the 'real' forest manager. It is believed that the most useful criticisms will result after such tests have been completed.

BIBLIOGRAPHY

Aberdeen University (1986). Costs of operations in Scotland for forest year 1984. In *Economic surveys of private forestry*. Department of Forestry, University of Aberdeen.

Aberdeen University (1987). Costs of operations in Scotland for forest year 1985. In *Economic surveys of private forestry*. Department of Forestry, University of Aberdeen.

Ackoff, R. L. (1979a). The future of Operational Research is past. *Journal of Operational Research Society* **30**, 93-104.

Ackoff, R. L. (1979b). Resurrecting the future of Operational Research. *Journal of Operational Research Society* **30**, 189-199.

Adams, D. M. and Ek, A. R. (1974). Optimizing the management of uneven-aged forest stands. *Canadian Journal of Forest Research* **4**, 274-287.

Allen, J. C. (1986). Multiobjective regional forest planning using the Noninferior Set Estimation (NISE) method in Tanzania and the United States. *Forest Science* **32**(2), 517-533.

Amidon, E. L. and Akin, G. S. (1968). Dynamic Programming to determine optimum levels of growing stock. *Forest Science* **14**(3), 287-291.

Arp, P. A. and Lavigne, D. R. (1982). Planning with Goal Programming: a case study for multiple-use of forested land. *Forest Chronicle* **58**(5), 225-232.

Arthur, L. M. (1977). Predicting scenic beauty of forest environments: some empirical tests. *Forest Science* **23**(2), 151-160.

Aubin, J. (1973). Multi-games and decentralization in management. In Cohrane, J. L. and Zeleny, M. (eds). *Multiple Criteria Decision Making*. University of South Carolina Press, South Carolina.

Baumgartner, T., Burns, T. R., DeVille, P. and Meeker, L. D. (1975). A systems model of conflict and change in planning systems with multiple objective evaluation and decision making. *General Systems* **20**, 167-183.

Bare, B. B. and Anholt, B. F. (1976). Selecting forest residue treatment alternatives using Goal Programming. *USDA Forest Service General Technical Report* **PNW-43**. Portland, Oregon.

Becker, G. S. (1965). A theory of allocation of time. *The Economic Journal* **75**, 493-517.

Bell, D. E., Keeney, R. L. and Raiffa, H. (1977). *Conflicting objectives in decisions*. Wiley, IIASA, International Series on Applied Systems Analysis, New York.

Bell, D. E. (1977). A decision analysis of objectives for a forest pest problem. In Bell, D. E., Keeney, R. L. and Raiffa, H. (eds) *Conflicting objectives in decisions*. Wiley, IIASA, International Series on Applied Systems Analysis, New York.

Bell, E. F. (1976). Goal Programming for land-use planning. *USDA Forest Service General Technical Report* **PNW-53**. Portland, Oregon.

Bell, E. F. (1977). Mathematical Programming in forestry. *Journal of Forestry* **75**, 317-319.

Benayoun, R., DeMontgolfier, J., Tergny, J. and Larichev, O. (1971). Linear Programming with multiple objective functions: STEP method (STEM). *Mathematical Programming* **1**, 366-375. North Holland.

Berry, J. K. (1987). Fundamental operations in computer-assisted map analysis. *International Journal of Geographical Information Systems* **1**(2), 119-136.

Berry, W. D. and Feldman, S. (1985). *Multiple Regression in practice*. Sage Publications, London.

Bertier, P. and DeMontgolfier, J. (1974). On Multicriteria Analysis: an application to a forest management problem. *METRA*, **13**(1), 33-46.

Bowes, M. D. and Loomis, J. B. (1980). A note on the use of travel cost models with unequal zonal populations. *Land Economics* **56**, 465-470.

Boyce, S. G. (1977). Management of eastern hardwood forests for multiple benefits (DYNAST-MB). *USDA Forest Service Research Paper* **SE-168**. Asheville, North Carolina.

Boyce, S. G. (1978). Management of forests for timber and related benefits (DYNAST-TM). *USDA Forest Service Research Paper* **SE-184**. Asheville, North Carolina.

Brasnett, N. V. (1953). *Planned management of forests*. George Allen and Unwin, London.

Brill, E. D., Chang, S. Y. and Hopkins, L. D. (1982). Modelling to generate alternatives: the HSJ approach and an illustration using a problem in land-use planning. *Management Science* **28**(3), 221-235.

Brodie, J. D., Adams, D. M. and Kao, C. (1978). Analysis of economic impacts on thinning and rotation for Douglas-fir, using Dynamic Programming. *Forest Science* **24**(4), 513-522.

Brodie, J. D. and Kao, C. (1979). Optimizing thinning in Douglas-fir with Three-Descriptor Dynamic Programming to account for accelerated diameter growth. *Forest Science* **25**(4), 665-672.

Brodie, J. D. and Haight, R. G. (1984). Optimization of silvicultural investment for several types of stand projection systems. *Canadian Journal of Forest Research* **15**, 188-191.

Brookshire, D. S., Randall, A. and Stoll, J. R. (1980). Valuing increments and decrements in natural resource service flows. *American Journal of Agricultural Economics* **62**(3), 478-488.

Brotherton, D. I. (1973). The concept of carrying capacity of countryside recreation areas. *Recreation News supplement* **6**, July 1973.

Brown, R. V. (1970). Do managers find decision theory useful? *Harvard Business Review* **48**, 78-89.

Brown, T. C. (1976). Alternative analysis for multiple-use management: a case study. *USDA Forest Service Research Paper* **RM-176,** Fort Collins, Colorado.

Brown, T. C. (1987). Production and cost of scenic beauty: examples for a Ponderosa Pine forest. *Forest Science* **33**(2), 394-410.

Brown, W. G. and Nawas, F. (1973). Impact of aggregation on the estimation of outdoor recreation demand functions. *American Journal of Agricultural Economics* **55**, 246-249.

Buongiorno, J. and Michie, B. R. (1980). A matrix model of uneven-aged forest management. *Forest Science* **26**, 609-625.

Buhyoff, G. J., Wellman, J. D. and Daniel, T. C. (1982). Predicting scenic quality for Mountain Pine Beetle and Western Spruce Budworm damaged forest vistas. *Forest Science* **28**(4), 827-838.

Buhyoff, G. J., Hull IV, R. B., Lien, J. N. and Cordell, H. K. (1986). Prediction of scenic quality for Southern Pine stands. *Forest Science* **32**(3), 769-778.

Canham, H. O. (1986). Comparable valuation of timber and recreation for forest planning. *Journal of Environmental Management* **23**, 335-339.

Cesario, F. J. and Knetch, J. L. (1970). Time bias in recreation benefit estimates. *Water Resources Research* **6**, 700-704.

Cesario, F. J. and Knetch, J. L. (1976). A recreation site demand and benefit estimation model. *Regional Studies* **10**, 97-104.

Chang, S. J. (1981). Determination of the optimal growing stock and cutting cycle for an uneven-aged stand. Forest Science 27(4), 739-744.

Chang, S. Y. and Buongiorno, J. (1981). A programming model for multiple-use forestry. *Journal of Environmental Management* **13**, 45-58.

Chappelle, D. E. and Nelson, T. C. (1964). Estimation of optimal stocking levels and rotation ages of Loblolly Pine. *Forest Science*, **10**(4), 471-502.

Chappelle, D. E., Mang, M. and Miley, R. C. (1976). Evaluation of timber RAM as a forest management planning model. *Journal of Forestry* **74**(5), 288-293.

Chappelle, D. E. (1977). Linear Programming for forest planning. In Convery, F. J. and Ralston, C. W. (eds) *Forestry and Long-Range Planning*. School of Forestry and Environmental Studies, Duke University, Durham, North Carolina.

Charnes, A., Cooper, W. W., Lewis, K. A. and Niehaus, R. J. (1976). A multi-objective model for planning equal employment opportunities. In Zeleny, M. (ed) *Multiple Criteria Decision Making: Kyoto 1975*. Springer-Verlag, N. York.

Chatterjee, S. and Price, B. (1977). *Regression analysis by example*. John Wiley and Sons, N.York.

Clark, R. and Stankey, G. (1979). The recreation opportunity spectrum: a framework for planning, management and research. *USDA Forest Service, General Technical Report* **PNW-98**. Portland, Oregon.

Clawson, M. (1959). *Methods of measuring the demand for and value of outdoor recreation*. Reprint 10, Resources for the Future, Washington, D.C.

Clawson, M. (1974). Economic trade-offs in multiple-use management of forest lands. *American Journal of Agricultural Economics* **56**(5), 919-926.

Clutter, J. L., Fortson, J. C., Pienaar, L.V., Brister, G. H. and Bailey, R. L. (1983). *Timber management. A quantitative approach.* John Wiley and Sons Inc., N. York.

Cohon, J. L. and Marks, D. H. (1973). Multi-objective screening models and water resource investment. *Water Resources Research* **9**(4), 826-836.

Cohon, J. L. and Marks, D. H. (1975). A review and evaluation of Multiobjective Programming Techniques. *Water Resources Research* **11**(2), 208-220.

Cohon, J. L. (1978). *Multiobjective Programming and Planning*. Academic Press, N. York.

Collins, R. and Hodge, I. (1984). Clustering visitors for recreation management. *Journal of Environmental Management* **19**, 147-158.

Connaughton, K. P. and Fight, D. R. (1984). Applying trade-off analysis to national forest planning. *Journal of Forestry* **82**(11), 680-683.

Convery, F. J. (1977). Benefit-Cost Analysis and forest planning. In Convery, F. J. and Ralston, C. W. (eds) *Forestry and Long-Range Planning*. School of Forestry and Environmental Studies, Duke University, Durham, North Carolina.

Cooper A. B. and Mutch, W. E. S. (1979). The management of red deer in plantations. In Ford, E.D., Malcolm, D. C. and Atterson, J. (eds) *The ecology of even-aged forest plantations*. Proceedings of the Meeting of Division I, IUFRO, Edinburgh, September 1978.

Costley, T. and Mackenzie, S. (1982). Distant visitors and local residents: the links between tourism and recreation in Scotland. In *Proceedings of the Countryside Recreation Research Advisory Group Conference 1982. University of Bath 22-23 September*. CRRAG, London.

Countryside Commission for Scotland (1986). *Forestry in Scotland. A policy paper.* Countryside Commission for Scotland, Edinburgh.

Crowe, S. (1973). Forestry and Land use. In Lovejoy, D. (ed.) *Land Use and Landscape Planning*. Leonard Hill Books, Great Britain.

Curtis, F. H. (1962). Linear Programming, the management of a forest property. *Journal of Forestry* **60**, 611-616.

Dane, C. W., Meador, N. C. and White, J. B. (1977). Goal Programming in land-use planning. *Journal of Forestry* **75**, 325-329.

DeKluyver, C. A., Daellenbach, H. G. and Whyte, A. G. D. (1980). A two-stage , Multiple Objective Mathematical Programming approach to optimal thinning and harvesting. *Forest Science* **26**(4), 674-686.

Dinkelbach, W. and Isermann, H. (1973). On decision making under multiple criteria and under incomplete information. In Cohrane, J. L. and Zeleny, M. (eds.) *Multiple Criteria Decision Making*. University of South Carolina Press, South Carolina.

Douglass, J. E. and Swank, W. T. (1972). Streamflow and modification through management of eastern forests. *USDA Forest Service Research Paper* **SE-94.**

Douglass, J. E. (1974). Watershed values. *Journal of Forestry* **72**, 617-621.

Douglass, R. W. (1975). *Forest Recreation.* Pergamon Press Inc., N. York.

Dyer, J. S. (1973). An empirical investigation of a man-machine interactive approach to the solution of the multiple criteria problem. In Cohrane, J. L. and Zeleny, M. (eds.) Multiple Criteria Decision Making. University of South Carolina Press, South Carolina.

Dyer, J. S. (1974). The effects of errors in the estimation of the gradient of the Frank-Wolfe algorithm with implications for Interactive Programming. *Operations Research* **22**(1), 160-174.

Dzieciolowski, R. (1970). Food carrying capacity of forest environments as an ecological problem. (In Polish). *Sylwan* **11**, 1-17.

Ecker, J. C. and Kouada, I. A. (1975). Finding efficient points for linear multiple objective programs. *Mathematical Programming* **8**, 375-378.

Ecker, J. C. and Kouada, I. A. (1978). Finding all efficient extreme points for multiple objective linear programs. *Mathematical Programming* **14**, 249-261.

Ecker, J. C. and Shoemaker, N. E. (1980). Multiple Objective Linear Programming and the trade-off compromise set. In Fandel, G. and Gal, T. (eds.) *Multiple Criteria Decision Making, Theory and Applications.* Springer-Verlag, N. York.

Edwards, P. N. and Christie, J. M. (1981). Yield models for forest management. *Forestry Commission Booklet* **48.** HMSO, London.

Eilon, S. (1980). The role of management science. *Journal of Operational Research Society* **31**, 17-28.

Evans, G. W. (1984). An overview of techniques for solving multiobjective mathematical programs. *Management Science* **30**(11), 1268-1282.

Evans, J. P. and Steuer, R. E. (1973). A revised Simplex Method for linear multiple objective programs. *Mathematical Programming* **5**(1), 54-72.

Fawcett, R. H. (1974a). An Introduction to Linear Programming. *Lecture Notes.* The Edinburgh School of Agriculture. University of Edinburgh.

Fawcett, R. H. (1974b). *Users guide to LP on EMAS.* The Edinburgh School of Agriculture. University of Edinburgh.

Fawcett, R. H. (1974c). Introduction to Linear Programming. The Modified Simplex Algorithm. *Lecture Notes.* The Edinburgh School of Agriculture. University of Edinburgh.

Field, D. B. (1973). Goal Programming for forest management. *Forest Science* **19**(2), 125-135.

Field, D. B. (1977). Linear Programming: out of the classroom and into the woods. *Journal of Forestry* **75**, 330-334.

Field, R. C., Dress, P. E. and Fortson, J. C. (1980). Complementary Linear and Goal Programming procedures for timber harvest scheduling. *Forest Science* **26**(1), 121-133.

Fishburn, P. C. (1974). Lexicographic orders, utilities and decision rules: a survey. *Management Science* **20**(11), 1442-1471.

Forestry Commission (1935). *Report of the National Forest Park Committee 1935.* HMSO, London.

Forestry Commission (1951). *Britain's Forests. Loch Ard.* HMSO, London.

Forestry Commission (1961). National Forest Parks. *Forestry Commission Booklet* **6**. HMSO, London.

Forestry Commission (1972). Wildlife conservation in Woodlands. *Forestry Commission Booklet* **29**. HMSO, London.

Forestry Commission (1973). Queen Elizabeth Forest Park. *Forestry Commission Guide*. HMSO, London.

Forestry Commission (1974). *Fifty-Fourth Annual Report and Accounts 1973-74*. HMSO, London.

Forestry Commission (1984a). The Forestry Commission's objectives. *Policy and Procedure Paper* **1**. HMSO, Edinburgh.

Forestry Commission (1984b). The Forestry Commission and Recreation. *Policy and Procedure Paper* **2**. HMSO, Edinburgh.

Forestry Commission (1984c). The Forestry Commission and Landscape Design. *Policy and Procedure Paper* **3**. HMSO, Edinburgh.

Forestry Commission (1984d). The Forestry Commission and Conservation. *Policy and Procedure Paper* **4**. HMSO, Edinburgh.

Forestry Commission (1985). The Policy for Broadleaved Woodlands. *Policy and Procedure Paper* **5**. HMSO, Edinburgh.

Forestry Commission (1986a). Forestry Practice. *Forestry Commission Bulletin* **14**. HMSO, London.

Forestry Commisssion (1986b). *Conservation Plan for Aberfoyle Forest District*. Unpublished. Aberfoyle Forest District Office.

Forestry Commission (1986c). *Aberfoyle Forest District: Broadleaved Woodland Plan*. Unpublished. Aberfoyle Forest District Office.

Forestry Commission (1986d). 1986 price-size relationships. *Planning and Economic Paper* **1**. Revised August 1986. HMSO, Edinburgh.

Forestry Commission (1987a). Timber production in Britain. *Forest Facts* **3**. HMSO, Edinburgh.

Forestry Commission (1987b). *Forestry Facts and Figures 1986-87*. Polton House Press, Lasswade.

Forestry Commission (1987d). Forest Parks. *Forestry Commission Leaflet.* HMSO, Edinburgh.

Forestry Commission (1987e). *67th Annual Report and Accounts 1986-87.* HMSO, London.

Forestry Commission (1988). *Woodland Grant Scheme.* HMSO, Edinburgh.

Gal, T. and Nedoma, J. (1972). Multi-parametric Linear Programming. *Management Science* **18**(7), 406-421.

Gearhart , W. B. (1979). Compromise solutions and estimation of the non-inferior set. *Journal of Optimization Theory and Applications* **28**, 29-47.

Geoffrion, A. M. (1967). Solving bicriterion mathematical programs. *Operations Research* **15**(1), 39-54.

Geoffrion, A. M., Dyer, J. S. and Feinberg, A. (1972). An interactive approach for multi-criterion optimization, with an application to the operation of an Academic Department. *Management Science* **19**(4), Part 1, 357-368.

Goodall, B. (1975). National forests and recreational opportunities. *Geographical Papers* **39**. Department of Geography, University of Reading.

Goodall, B. and Whittow, J. B. (1975). Recreation requirements and forest opportunities. *Geographical Papers* **37**. Department of Geography, University of Reading.

Grayson, A. J., Sidaway, R. M. and Thompson, F. P. (1973). Some aspects of recreation planning in the Forestry Commission. *Forestry Commission Research and Development Paper* **95**. HMSO, London.

Grayson, C. J. (1973). Management science and business practice. *Harvard Business Review* **51**, 41-48.

Green, P. (1973). Multidimensional scaling and conjoint measurement in the study of choice among multiattribute alternatives. In Cohrane, J. L. and Zeleny, M. (eds.) *Multiple Criteria Decision Making*. University of South Carolina Press, South Carolina.

Gregory, G. R. (1955). An economic approach to multiple use. *Forest Science* **1**(1), 6-13.

Gum, R. L. and Martin, W. E. (1975). Problems and solutions in estimating the demand for and value of rural outdoor recreation. *American Journal of Agricultural Economics* **57**, 558-566.

Hagenstein, P. R. and Dowdle, B. (1962). A theoretical model for examining forest land use alternatives. *Journal of Forestry* **60**, 187-191.

Haimes, Y. Y. and Hall, W. A. (1974). Multi-objectives in water resources systems analysis: the Surrogate Worth Trade-off method. *Water Resources Research* **10**(4), 615-624.

Hall, W. A. and Haimes, Y.Y. (1976). The Surrogate Worth Trade-off method with multiple decision-makers. In Zeleny, M. (ed.) *Multiple Criteria Decision Making:Kyoto 1975*. Springer-Verlag, N. York. 207-233.

Hamill, L. (1971). Classification of forest land for recreational potential and scenery. *Forest Chronicle* **47**, 149-153.

Hanley, N. and Common, M. (1987). *Estimating the recreation, wildlife and landscape benefits of forestry: preliminary results from a Scottish study.* Paper presented to the conference on Agriculture and Forestry in the European environment, 16-19 September 1987 at the University of Newcastle-on-Tyne.

Harrison, T. (1983). *Design and development of a decision support system for forest management planning with multiple objectives.* Unpublished Ph. D. thesis. University of Tennesse, Department of Management Science, Knoxville, pp 168.

Hastings, N. A. J. and Peacock, J. B. (1974). *Statistical distributions.* Butterworth and Co., London.

Hecock, R. (1970). Recreation behaviour patterns as related to site characteristics of beaches. *Journal of Leisure Research* **12**(4), 237-250.

Hellman. O. (1982). A mathematical model for an energy forest. *Management Science* **28**(11), 1247-1257.

Hill, M. (1973). *Planning for multiple objectives- an approach to the evaluation of transportation plans.* Monograph 5. Regional Science Research Institute, Philadelphia, Pennsylvania.

Hockin, R., Goodall, B. and Whittow, J. (1977). The site requirements and planning of outdoor recreation activities. *Geographical Papers* **54**. Department of Geography, University of Reading.

Hof, J. G. and King, D. A. (1982). On the necessity of simultaneous recreation demand equation estimation. *Land Economics* **58**(4), 547-552.

Hof, J. G., Marose, R. K. and King, D. A. (1985). Potential pitfalls in renewable resource decision making that utilizes convex combinations of discrete alternatives.*Western Journal of Agricultural Economics* **10**(2), 391-400.

Hof, J. G., Pickens, J. B. and Bartlett, E. T. (1986). A MAXMIN approach to nondeclining yield timber harvest scheduling problems. *Forest Science* **32**(3), 653-666.

Horne, A. I. D. and Whitlock, M. D. (1984). The Forestry Commission subcompartment database. *Forestry Commission Research Information Note* **94**. Alice Holt Lodge, Surrey.

Horne, A. I. D. (1984). The Forestry Commission subcompartment database. *Forestry Commission Research Information Note* **95**. Alice Holt Lodge, Surrey.

Hotvedt, J. E., Leuschner, W. A. and Buhyoff, G. J. (1981). A heuristic weight determination procedure for goal programs used for harvest scheduling models.*Canadian Journal of Forest Research* **12**, 292-298.

Hull IV, R. B. and Buhyoff, G. J. (1986). The scenic beauty temporal distribution method: an attempt to make scenic beauty compatible with forest planning efforts. *Forest Science* **32**(2), 271-286.

Hwang, C. and Masud, A. (1979). Multiple Objective Decision Making Methods and Applications. *Lecture Notes in Economics and Mathematical Systems* **164**. Springer-Verlag, New York.

Hyberg, B. T. (1987). Multiattribute decision theory and forest management: a discussion and application. *Forest Science* **33**(4), 835-845.

Ignizio, J. P. (1982). Linear Programming in single and multiple objecive systems. Prentice-Hall, Engelwood Cliffs, N.Jersey.

Ignizio, J. P. (1983). Generalized Goal Programming. *Computers and Operations Research* **10**(4), 277-289.

Jackson, B. J. (1971). A Linear Programming model of the U. K. Forest Products Sector. In Wardle, P. A. (ed.) Operational Research and the Managerial Economics of Forestry. *Forestry Commission Bulletin* **44**. HMSO, London.

James, G. A. and Rich, J. L. (1966). Estimating recreation use on a complex of developed sites. *USDA Forest Service Research Note* **SE-64**. Asheville, North Carolina.

Johanson, P. O. (1984). Approaches to determing monetary welfare change measures. *Canadian Journal of Forest Research* **15**, 126-131.

Johnson, K. N. and Scheurman, H. L. (1977). Techniques for prescribing optimal timber harvest and investment under different objectives-discussion and synthesis. *Forest Science Monograph* **18**. Supplement to Forest Science **23** (1), March 1977.

Johnstone, M. and Tivy, J. (1980). Assessment of the physical capability of land for rural recreation. In Thomas, M. F. and Coppock, J. T. (eds.) *Land assessment in Scotland.* Aberdeen University Press. Great Britain.

Jordi, K. C. and Peddie, D. (1988). A wildlife management problem: a case study in Multiple-objective Linear Programming. *Journal of Operational Research Society* **39**(11), 1011-1020.

Kao, C. and Brodie, J. D. (1979). Determination of optimal thinning entry interval using Dynamic Programming. *Forest Science* **25**(4), 672-674.

Kao, C. (1982). Optimal stocking levels and rotation under risk. *Forest Science* **28**(4), 711-719.

Karwan, K. R. and Wallace, W. A. (1980). A comparative evaluation of Conjoint Measurement and Goal Programming as aids in decision making for marine environmental protection. In Fandel, G. and Gal, T. (eds.) *Multiple Criteria Decision Making Theory and Applications*. Springer-Verlag, N.York.

Keeney, R. L. (1972). Utility functions for multiattributed consequences. *Management Science* **18**(5), Part 1, 276-287.

Kellert, S. R. (1984). Assessing wildlife and environmental values in Cost-Benefit Analysis. *Journal of Environmental Management* **18**, 355-363.

Kent, B. M. (1980). Linear Programming in land-management planning on national forests. *Journal of Forestry* **78**, 469-471.

Kidd, W. E., Thompson, E. F. and Hoepner, P. H. (1966). Forest regulation by Linear Programming -a case study. *Journal of Forestry* **64**, 611-613.

King, D. A. and Hof, J. G. (1985). Experiential commodity definition in recreation travel cost models. *Forest Science* **31**(2), 519-529.

King, D. A., Bugarsky, D. J. and Shaw, W. W. (1986). *Contingent valuation: an application to wildlife*. Paper presented at the 18th IUFRO World Congress, Ljubljana, Yugoslavia.

Koch, N. E. (1984). Project 'Forest and Folk': a summary. In Saastamoinen, O., Hultman, S. G., Koch, N. E. and Mattsson, L. (eds.) *Multiple-Use Forestry in the Scandinavian countries*. Proceedings of the Scandinavian symposium held in Rovaniemi and Saariselka, Finland, September 13-17, 1982. Helsinki, Finland.

König, E. and Gossow, H. (1979). Even-aged stands as habitat for deer in Central Europe. In Ford, E. D., Malcolm, D. C. and Atterson, J. (eds.) *The Ecology of even-aged forest plantations*. Proceedings of the Meeting of Division I, IUFRO, September 1978, Edinburgh.

Kornbluth, J. S. H. and Steuer, R. E. (1980). On computing the set of all weakly efficient vertices in multiple objective Linear Fractional Programming. In Fandel, G. and Gal, T. (eds.) *Multiple Criteria Decision Making Theory and Applications*. Springer-Verlag, N. York.

Kornbluth, J. S. H. and Steuer, R. E. (1981). Goal Programming with linear fractional criteria. *European Journal of Operational Research* **8**, 58-65.

La Page, W. F. (1962). Recreation and the forest site. *Journal of Forestry* **60**(5), 319-321.

Legg, C. J. (1973). *Pattern Analysis. An examination of the methods used when studying plant populations*. B. Sc. Dissertation, U.C.W., Aberystwyth.

Lembersky, M. R. and Johnson, K. N. (1975). Optimal policies for managed stands: an infinite horizon Markov decision process approach. *Forest Science* **21**(2), 109-122.

Liittschwager, J. M. and Tcheng, T. H. (1967). Solution of a large-scale forest scheduling problem by Linear Programming decomposition. *Journal of Forestry* **65**, 644-646.

Lloyd, R. D. (1969). Economics of multiple use. *Proceedings, Conference on Multiple Use of Southern Forests, Pine Mountain*. Georgia.

Loomis, J. B. and Walsh, R. G. (1986). Assessing wildlife and environmental values in Cost-Benefit Analysis: a state of the art. *Journal of Environmental Management* **22**, 125-131.

Loucks, D. P. (1964). The development of an optimal program for sustained-yield management. Journal of Forestry 62, 485-490.

Leuschner, W. A., Porter, J. R., Reynolds, M. R. and Burkhart, H. E. (1975). A Linear Programming model for multiple-use planning. *Canadian Journal of Forest Research* **5**, 485-491.

Lucas, R. C. (1963). Bias in estimating recreationists length of stay for sample interviews. *Journal of Forestry* **61**, 912-914.

Luenberger, D. G. (1973). *Introduction to Linear and Non-linear Programming* . Addison-Wesley, Inc. Reading, Massachusetts.

MacCrimmon, K. R. (1973). An overview of multiple objective decision making. In Cohrane J. L. and Zeleny, M. (eds.) *Multiple Criteria Decision Making*. University of South Carolina Press. South Carolina.

Marglin. S. (1967). *Public Investment Criteria.* Allen and Unwin, London.

McConnel, K. E. (1975). Some problems in estimating the demand for outdoor recreation. *American Journal of Agricultural Economics* 57, 330-334.

McConnen, R. J., Navon, D. I. and Amidon, E. L. (1966). Efficient development and use of forest lands: an outline of a prototype computer-oriented system for operational planning. In HMSO (ed.) Mathematical Models in Forest Management. Proceedings of the meeting held athe University of Edinburgh on 12th and 13th April 1965. *Forestry Commission Forest Record* **59.** England.

Mendoza, G. A., Bare, B. B. and Campbell, G. E. (1987). Multiobjective Programming for generating alternatives: a multiple-use planning example. *Forest Science* **33**(2), 458-468.

Mercer, D. (1981). Trends in recreational participation. In Mercer, D. (ed.) *Outdoor Recreation: Australian Perspectives.* Sorett, Melbourne.

Mitchell, B., Staines, B. W. and Welsh, D. (1977). *Ecology of red deer. A research review relevant to their management in Scotland.* Institute of Terrestrial Ecology, Cambridge.

Morse, J. N. (1980). Reducing the size of the nondominated set. Pruning by clustering. *Computers and Operations Research* **7**, 55-66.

Mutch, W. E. S. (1968). Public Recreation in National Forests. *Forestry Commission Booklet* **21.** HMSO, England.

Mutch, W. E. S., Lockie, J. D. and Cooper, A. B. (1976). *Red deer in South Ross.* Department of Forestry and Natural Resources. University of Edinburgh.

Nature Conservancy Council (1986). *Nature conservation and afforestation in Britain.* Nature Conservancy Council.

Nautiyal, J. C. and Pearse, P. H. (1967). Optimizing the conversion to sustained yield- a Programming solution. *Forest Science* **13**(2), 131-139.

Navon, D. I. (1971). Timber RAM, a long -range planning method for commercial timber lands under multiple-use management. *USDA Forest Service Research Paper* **PNW-70**. Berkeley, California.

Osmaston, F. C. (1968). *The management of forests.* Hafner Publishing Company, N.York.

Osteen, C. and Chappelle, D. E. (1982). Forest management options and policy implications in the Kallamazoo River Basin of Michigan. *Journal of Forestry* **80**, 287-290.

Peterken, G. (1977). General management principles for nature conservation in British woodlands. *Forestry* **50**(1), 27-48.

Peterken, G. (1985). *Woodland conservation and management.* Chapman and Hall, London.

Phillip, J. (1972). Algorithms for vector maximization problems. *Mathematical Programming* **2**, 207-229.

Phillips, J. and Mutch, W. E. S. (1974). *Red deer in woodand.* Published by the authors, Edinburgh.

Pritchard, M. A. (1986). Operational planning and control in the Forestry Commission. The Forest District computer system. In Mason, W. L. and Muetzelfeldt, R. I. (eds.) *Computers in Forestry.* Institute of Chartered Foresters, Edinburgh.

Ratcliffe, P.R. (1984). Population dynamics of red deer (Cervus elaphus, L.) in Scottish commercial forests. *Proceedings of the Royal Society of Edinburgh* **82B**, 291-302.

Ratcliffe, P. R., Hall, J. and Allen, J. (1986). Computer predictions of sequential growth changes in commercial forests as an aid to wildlife management, with reference to red deer. *Scottish Forestry* **40**(2), 79-83.

Ratcliffe, P. R. (1987). The management of red deer in upland forests. *Forestry Commission Bulletin* **71**. HMSO, London.

Rideout, D. and Hof, J. (1987). Cost sharing in multiple-use forestry: a Game Theoretic Approach. *Forest Science* **33**(1), 81-88.

Riiters, K., Brodie, J. D. and Hann, D. W. (1982). Dynamic Programming for optimization of timber production and grazing in Ponderoza Pine. *Forest Science* **28**(3), 517-526.

Roise, J. P. (1986a). A Non-linear Programming approach to stand optimization. *Forest Science* **32**(3), 735-748.

Roise, J. P. (1986b). An approach for optimizing residual diameter class distributions when thinning even-aged stands. *Forest Science* **32**(4), 871-881.

Romero, C. and Rehman, T. (1984). Goal Programming and multiple criteria decision-making in farm planning: an expository analysis. *Journal of Agricultural Economics* **35**, 177-190.

Romero, C. and Rehman, T. (1985). Goal Programming and multiple criteria decision-making in farm planning: some extensions. *Journal of Agricultural Economics* **36**, 171-185.

Rorres, C. (1978). A Linear Programming approach to the optimal sustainable harvesting of a forest. *Journal of Environmental Management* **6**, 245-254.

Rose, D. W., Leary, R. A. and Chen, C. M. (1981). Maximum cubic volume production through easily derived optimum thinning schedules. *Journal of Forestry* **79**, 32-35.

Rowan, A. A. (1977). Terrain classification. *Forestry Commission Forest Record* **114**, HMSO, London.

Roy, B. (1971). Problems and methods with multiple objective functions. *Mathematical Programming* **1**, 239-266.

Roy, B. (1973). How outranking relation help multiple criteria decision-making. In Cohrane, J. L. and Zeleny, M. (eds.) *Multiple Criteria Decision Making*. University of South Carolina Press. South Carolina.

Schreuder, H. T. (1970). Point sampling theory in the framework of equal probability cluster sampling. *Forest Science* **16**, 240-246.

Schreuder, H. T., Tyre, G. L. and James, G. A. (1975). Instant and interval-count sampling: two new techniques for estimating recreation use. *Forest Science* **21**(1), 40-44.

Schroeder, H. and Daniel, T. C. (1981). Progress in predicting the perceived scenic beauty of forest landscapes. *Forest Science* **27**(1), 71-80.

Schroeder, L. D., Sjoquist, D. L. and Stephan, P. E. (1986). *Understanding regression analysis. An introductory guide*. Sage Publications, London.

Schuler, A. T. and Meadows, J. C. (1975). Planning resource use on national forests to achieve multiple objectives. *Journal of Environmental Management* **3**, 351-366.

Schuler, A. T., Webster, H. H. and Meadows, J. C. (1977). Goal Programming in forest management. *Journal of Forestry* **75**, 320-324.

Sengupta, S. S., Podrebarac, M. L. and Fernando, T. D. H. (1973). Probabilities in multi-objective linear programs. In Cohrane, J. L. and Zeleny, M. (eds.) *Multiple Criteria Decision Making*. University of South Carolina Press. South Carolina.

Sieränen, T. (1984). Comparison of different methods in the inventory of urban forest recreation. In Saastamoinen, O., Hultman, S. G., Koch, N. E. and Mattsson, L. (eds.) *Multiple-use forestry in the Scandinavian countries*. Proceedings of the Scandinavian symposium held in Rovaniemi and Saariselka, Finland, September 13-17, 1982. Helsinki, Finland.

Silverman, J., Steuer, R. E. and Whisman, A. W. (1985). *A multi-period, multiple criteria optimization system for manpower planning*. Working paper series. College of Business Administration. The University of Georgia.

Simon, H. (1960). *The new science of management decision.* Harper and Row Publishers, N. York.

Sprague, R. H. and Carlson, E. D. (1982). *Building effective decision support systems*. Prentice-Hall, Inc., Englewood Cliffs, N. Jersey.

Staines, B. W. and Welsh, D. (1984). Habitat selection and impact of red (Cervus elaphus L.) and roe (Capreolus capreolus L.) deer in a Sitka Spruce plantation. *Proceedings of the Royal Society of Edinburgh* **82B**, 303-319.

Stankey, G. H. (1982). The role of management in wilderness and natural-area preservation. *Environmental Conservation* **9**(2), 149-155.

Steuer, R. E. (1975a). A five phase procedure for implementing a vector-maximum algorithm for Multiple Objective Linear Programming. In Thiriez, H. and Zionts, S. (eds.) *Multiple Criteria Decision Making*. Joay-en-Josas, France, Springer-Verlag, Heidelberg.

Steuer, R. E. (1975b). ADBASE: an adjacent efficient basis algorithm for vector-maximum and interval-weighted-sums Linear Programming problems (in FORTRAN). *Journal of Marketing Research* **12**, 454-455.

Steuer, R. E. (1976). Multiple Objective Linear Programming with interval criterion weights. *Management Science* **23**, 305-316.

Steuer, R. E. (1977). An Interactive Multiple Objective Linear Programming procedure. In Starr, M. K. and Zeleny, M. (eds.) Multiple Criteria Decision Making. *Studies in Management Sciences* **6**, 178-190. North Holland, Amsterdam.

Steuer, R. E. and Schuler, A. T. (1979). An Interactive Multiple Objective Linear Programming approach to a problem in forest management. *Forest Ecology and Management* **2**, 191-205.

Steuer, R. E. and Harris, F. W. (1980). Intra-set point generation and filtering in decision and criterion space. *Computers and Operations Research* **7**, 41-53.

Steuer, R. E. and Choo, E. U. (1983). An Interactive Weighted Tchebycheff procedure for Multiple Objective Programming. *Mathematical Programming* **26**, 326-344. North Holland.

Teeguarden, D. E. (1979). Managing timber resources. In Duerr, W. A., Teeguarden, D. E., Christiansen, N. B. and Guttenberg, S. (eds.) *Forest Resource Management. Decision Making cases and principles.* W. B. Saunders Co. Philadelphia.

Teeter, L. D. and Dyer, A. A. (1986). A multiattribute utility model for incorporating risk in fire management planning. *Forest Science* **32**(4), 1032-1048.

Thomas, H. and Samson, D. (1986). Subjective aspects of the Art of Decision Analysis: exploring the role of Decision Analysis in decision structuring, decision support and policy dialogue. *Journal of Operational Research Society* **37**(3), 249-265.

Tivy, J. (1973). The concept and determination of carrying capacity of recreational land in the U.S.A. *Countryside Commission for Scotland Occ. Paper* **3**.

Tivy, J. (1980). *The effect of recreation on freshwater lochs and reservoirs in Scotland.* Countryside Commisssion for Scotland. Perth.

Törn, A. A. (1980). A sampling-search clustering approach for exploring the feasible/efficient solutions of MCDM problems. *Computers and Operations Research* **7**, 67-80.

Tourism and Recreation Research Unit (TRRU) (1974). *TRIP SERIES No. 1. System description. Research Report* **11**. University of Edinburgh. Edinburgh.

Tourism and Recreation Research Unit (TRRU) (1978). *STARS SERIES No. 4. The woodland visitor. Research Report* **20**. University of Edinburgh. Edinburgh.

Usher, M. B. (1966). A matrix approach to the management of renewable resources, with special reference to selection forests. *Journal of Applied Ecology* **3**, 355-367.

Usher, M. B. (1976). Extensions to models, used in renewable resource management, which incorporate an arbitrary structure. *Journal of Environmental*

Management **4**, 123-140.

Vaugham. W. J. and Russell, C. S. (1984). The role of recreation resource availability variables in recreation participation analysis. *Journal of Environmental Management* **19**, 185-196. Washington, D.C.

Wagar, J. A. (1964). The carrying capacity of wild lands for recreation. *Forest Science Monograph* **7**.

Walker, H. D. (1985). An alternative approach to Goal Programming. *Canadian Journal of Forest Research* **15**, 319-325.

Walter, G. R. (1978). Market methods of multiple-use reconciliation. *Journal of Environmental Management* **7**, 291-296.

Wardle, P. A. (1966). Linear Programming studies. In HMSO (ed.) Mathematical Models in Forest Management. Proceedings of the meeting held at the University of Edinburgh on 12th and 13th April 1965. *Forestry Commission Forest Record* **59**.

Wardle, P. A. (1970). Operational Research and the design of a management control system for a forestry enterprise. In Wardle, P. A. (ed.) Operational Research and the Managerial Economics of Forestry. *Forestry Commission Bulletin* **44**. HMSO, London.

Ware, G. O. and Clutter, J. L. (1971). A mathematical programming system for the management of industrial forests. *Forest Science* **17**(4), 428-445.

Wierzbicki, A. P. (1980). The use of reference objectives in multiobjective optimization. In Fandel, G. and Gal, T. (eds.) Multiple Criteria Decision Making Theory and Application. Springer-Verlag, N.York.

**

Yu, P. L. (1973). A class of solutions for group decision problems. *Management Science* **19**(8), 936-946.

Yu, P. L. (1974). Cone convexity, cone extreme points and nondominated solutions in decision problems with multiobjectives. *Journal of Optimization Theory and Applications* **14**(3), 319-377.

Yu, P. L. and Leitmann, G. (1974). Nondominated decisions and cone convexity in dynamic multi-criteria decision problems. *Journal of Optimization Theory and Applications* **14**(5), 573-584.

Yu, P. L. and Leitmann, G. (1976). Compromise solutions, domination structures and Salukvadze's solution. In Leitmann, G. (ed.) Multicriteria Decision Making and Differential Games. Plenum, N.York.

Zadeh, L. A. (1963). Optimality and non-scalar performance criteria. *IEEE Transactions Automatic Control* **8**, 59-60.

Zadeh, L. A. (1973). Outline of a new approach to the analysis of complex systems and decision processes. In Cohrane J. L. and Zeleny, M. (eds.) *Multiple Criteria Decision Making*. University of South Carolina Press. South Carolina.

Zeleny, M. (1973). Compromise Programming. In Cohrane, J. L. and Zeleny, M. (eds.) *Multiple Criteria Decision Making*. University of South Carolina Press. South Carolina.

Zeleny, M. (1974). *Multiobjective Linear Programming*. Springer-Verlag, N. York.

Zeleny, M. (1976a). The theory of the Displaced Ideal. In Zeleny, M. (ed.) *Multiple Criteria Decision Making:Kyoto 1975*. Springer-Verlag, N.York.

Zeleny, M. (1976b).Multicriteria Simplex Method: a FORTRAN routine. In Zeleny, M. (ed.) *Multiple Criteria Decision Making: Kyoto 1975*. Springer-Verlag, N. York.

Zeleny, M. (1982). *Multiple Criteria Decision Making*. McGraw-Hill, N. York.

Zimmerman, H. J. (1978). Fuzzy Programming and Linear Programming with several objective functions. *Fuzzy Sets and Systems* **1**, 45-55.

Zionts, S. and Wallenius, J. (1976). An Interactive Programming method for solving the multiple criteria problem. *Management Science* **22**(6), 652-663.

Zionts, S. (1980). Methods for solving management problems involving multiple objectives. In Fandel, G. and Gal, T. (eds.) *Multiple Criteria Decision Making Theory and Applications*. Springer-Verlag, N. York.

Zionts, S. and Wallenius, J. (1983). An Interactive Multiple Objective Linear Programming method for a class of underlying nonlinear utility functions. *Management Science* **29**(5), 519-529.

* Knuchel, H. (1953). *Planning and control in the managed forest.* Translated by M. L. Anderson. Oliver and Boyd, Edinburgh.

** Willis, K. G. and Benson, J. F. (1989). Recreational Values of Forests. *Forestry* **62**, 93-110.

APPENDICES

APPENDIX 1

Coded format for timber production timing under:

1) the delayed by 5 years thinning regime
2) the extended rotation by 10 years thinning regime
3) the extended rotation by 15 years thinning regime
4) the extended rotation by 5 years thinning regime
5) the marginal thinning regime
6) the non-thinning regime

Coded format for timber production timing under the delayed by 5 years thinning regime

```
16
 3 10
SS WSS QSS
 6  0000000000 0000000000 0000000000 0000000100 0010000100 0010000100 0000020000 0030000000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 2000030000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000010 0001000010 0001000010 0001000230 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000001000 0100001000 0100001000 0002003000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000010000 1000010000 1000010000 2000030000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000100001 0000100001 0000000200 0000300000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0001000010 0001000010 0000020030 0000000000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0010000100 0010000100 0000200000 0030000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0010000100 0010000100 0002000300 0000000000 0000000000 0000000000 0000000000 0000000000
 4  9
NS OMS  XS  MC
 6  0000000000 0000000000 0000000000 0000000001 0000000100 0010000100 0010000100 0000020000 0030000000 0000000000
 8  0000000000 0000000000 0000000000 0000010000 0100001000 0100001000 0100001000 0200000000 0300000000 0000000000
10  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000002 0000000300 0000000000 0000000000
12  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 0002000000 0000030000 0000000000 0000000000
14  0000000000 0000000000 0000000010 0001000010 0001000010 0001000020 0000000000 0003000000 0000000000 0000000000
16  0000000000 0000000000 0000000100 0010000100 0010000100 0000200000 0000000000 0000000300 0000000000 0000000000
18  0000000000 0000000000 0000001000 0100001000 0100001000 0020000000 0000000000 0300000000 0000000000 0000000000
20  0000000000 0000000000 0000010000 1000010000 1000010000 0200000000 0000030000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000100001 0000100001 0000100000 2000000000 0000300000 0000000000 0000000000 0000000000
 3  6
SP WEP  XP
 4  0000000000 0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100000 0200000000 0000000003
 6  0000000000 0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0020000000 0000000300 0000000000
 8  0000000000 0000000000 0000000000 0001000010 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000
10  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000020000 0000300000 0000000000 0000000000
12  0000000000 0000000000 0000000100 0010000100 0010000100 0010000002 0000000300 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000010000 1000010000 1000010000 1000020000 0000000000 3000000000 0000000000 0000000000
 6  8
CP AUP MOP BIP RAP PDP
 6  0000000000 0000000000 0000000000 0000000100 0000001000 0100001000 0100020000 0300000000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0010000000 1000010000 1000010000 0200000000 3000000000 0000000000 0000000000
10  0000000000 0000000000 0000000001 0000010000 1000010000 1000010000 3200000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000100 0010000100 0010000100 0010000020 0030000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000010000 1000010000 1000010000 1000200000 3000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000100001 0000100001 0000100000 0200000003 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0001000010 0001000010 0001000020 0000000030 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0010000100 0010000100 0010000200 0000000300 0000000000 0000000000 0000000000 0000000000
 3  6
LP MAP SLP
 4  0000000000 0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000200003 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0000010000 1000010000 1000010000 1000000200 0000000000 3000000000 0000000000
 8  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 0200000000 3000000000 0000000000 0000000000
10  0000000000 0000000000 0000000100 0010000100 0010000100 0010000300 0200000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000010000 1000010000 1000010000 1000002000 3000000000 0000000000 0000000000 0000000000
```

(Continued)

```
14  0000000000 0000000000 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000 0000000000 0000000000
 2  6
JL  HL
 4  0000000000 0000000000 0000000000 1000000010 0001000010 0001000000 2003000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000001000 0010000100 0010000100 0030020000 0000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0001000010 0001000010 0001000010 0003020000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0100001000 0100001000 0100003000 0020000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000001 0000100001 0000100001 0000100023 0000000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000010 0001000010 0001000010 0003020000 0000000000 0000000000 0000000000 0000000000 0000000000
 1  9
DF
 8  0000000000 0000000000 0000000000 0010000001 0000100001 0000100001 0002000003 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000001 0000010000 1000010000 1000010002 0000030000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000100 0010000100 0010000100 0000200000 0030000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000010000 1000010000 1000010002 0000000000 3000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000020 0000000030 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0010000100 0010000100 0010002000 0000000300 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0100001000 0100001000 0100020000 0000003000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0100001000 0100001000 0100020000 0300000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 1000010000 1000010000 1000200000 3000000000 0000000000 0000000000 0000000000 0000000000
 1  5
EL
 4  0000000000 0000000000 0000000000 0100001000 0100001000 0100000002 0300000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000010000 1000010000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0100001000 0100001000 0100001000 0002003000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000001 0000100001 0000100001 0000100023 0000000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000100 0010000100 0010000100 0000200300 0000000000 0000000000 0000000000 0000000000 0000000000
 1  7
WH
12  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0000020000 0000000300 0000000000 0000000000
14  0000000000 0000000000 0000010000 1000010000 1000010000 1000010002 0000000000 0000030000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000010 0000200000 0000000000 0003000000 0000000000 0000000000
18  0000000000 0000000000 0100001000 0100001000 0100001000 0200000000 0000003000 0000000000 0000000000 0000000000
20  0000000000 0000000000 1000010000 1000010000 1000000200 0000000000 3000000000 0000000000 0000000000 0000000000
22  0000000000 0000000001 0000100001 0000100001 0000002000 0000000003 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000010 0001000010 0001000010 0000020000 0003000000 0000000000 0000000000 0000000000 0000000000
 4  7
RC  LC LEC JCR
12  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000020000 0000300000 0000000000 0000000000
14  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0020000000 0030000000 0000000000 0000000000
16  0000000000 0000000000 0000010000 1000010000 1000010000 1000010002 0000000000 3000000000 0000000000 0000000000
18  0000000000 0000000000 0001000010 0001000010 0001000010 0000002000 0000000030 0000000000 0000000000 0000000000
20  0000000000 0000000000 0010000100 0010000100 0010000100 0002000000 0030000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0100001000 0100001000 0100001000 2000000000 0300000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 1000010000 1000010000 1000000200 0000000000 3000000000 0000000000 0000000000 0000000000
 3 10
GF  RSQ WSQ
12  0000000000 0000000000 0000001000 0100001000 0100001000 0100002000 0300000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000100001 0000100001 0000100001 0002000003 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000000 2000000030 0000000000 0000000000 0000000000 0000000000
```

(Continued)

```
18   0000000000 0000000000 0010000100 0010000100 0010000020 0000000300 0000000000 0000000000 0000000000 0000000000
20   0000000000 0000000000 0100001000 0100001000 0100002000 0000003000 0000000000 0000000000 0000000000 0000000000
22   0000000000 0000000000 1000010000 1000010000 1000002000 0000030000 0000000000 0000000000 0000000000 0000000000
24   0000000000 0000000000 1000010000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000 0000000000
26   0000000000 0000000001 0000100001 0000100001 0000020003 0000000000 0000000000 0000000000 0000000000 0000000000
28   0000000000 0000000001 0000100001 0000100001 0000200003 0000000000 0000000000 0000000000 0000000000 0000000000
30   0000000000 0000000010 0001000010 0001000010 0000200030 0000000000 0000000000 0000000000 0000000000 0000000000
 3   7
NF  ESF  XF
10   0000000000 0000000000 0000000000 0001000010 0001000010 0001000010 0020000000 0000000030 0000000000 0000000000
12   0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 0002000000 0000000000 3000000000 0000000000
14   0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0020000000 0003000000 0000000000 0000000000
16   0000000000 0000000000 0000001000 0100001000 0100001000 0100000020 0000000000 0300000000 0000000000 0000000000
18   0000000000 0000000000 0000100001 0000100001 0000100001 0000020000 0000000003 0000000000 0000000000 0000000000
20   0000000000 0000000000 0010000100 0010000100 0010000100 0020000000 0000000300 0000000000 0000000000 0000000000
22   0000000000 0000000000 0100001000 0100001000 0100001000 2000000000 0000003000 0000000000 0000000000 0000000000
 3   3
OK  POK  SOK
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000000003
 6   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000300000 0000000000
 8   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000200000 0000300000 0000000000 0000000000
12   4
BE  ROC   SC   LI  CLI  SLI  LLI   EM  EEM  WEM  SEM  HBM
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000
 6   0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000
 8   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000300000
10   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000 0000300000 0000000000
10   4
SY  NOM   AH   BI  HCH   AR  CAR  GAR   XB   MB
 4   0000000000 0000000000 0000100001 0000100001 0000200000 0000300000 0000000000 0000000000 0000000000 0000000000
 6   0000000000 0000000001 0000100001 0000100001 0000400000 0000000000 0000000000 0000000000 0000000000 0000000000
 8   0000000000 0000000001 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000
10   0000000000 0000100001 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000
 2   5
OBN  PRN
10   0000000000 0000000000 0010000100 0010000100 0020000300 0000000000 0000000000 0000000000 0000000000 0000000000
12   0000000000 0000000000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000 0000000000 0000000000
14   0000000000 0000000010 0001000020 0003000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
16   0000000000 0000000100 0010000400 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
18   0000000000 0000001000 0100004000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
```

Key Note: Each value represents one time unit (i.e. 1 year).
0 = no activity, 1 = year of thinning, 2 = year of felling,
3 = year of maximum mean annual increment, 4 = when 2 and 3 coincide.

Coded format for timber production under the extended rotation by 10 years thinning regime

```
16
 3 10
SS WSS QSS
 6  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0030020000 0000000000 0000000000
 8  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000030 0200000000 0000000000 0000000000
10  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000030000 2000000000 0000000000 0000000000
12  0000000000 0000000000 0001000010 0001000010 0001000010 0001000030 0001000200 0000000000 0000000000 0000000000
14  0000000000 0000000000 0100001000 0100001000 0100001000 0100003000 0002000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 1000010000 1000010000 1000010000 1000030000 2000000000 0000000000 0000000000 0000000000
18  0000000000 0000000001 0000100001 0000100001 0000100001 0000300200 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000010 0001000010 0001000010 0001000030 0000020000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000100 0010000100 0010000100 0010000300 0000200000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000100 0010000100 0010000100 0010000300 0002000000 0000000000 0000000000 0000000000 0000000000
 4  9
NS OMS  XS  MC
 6  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000320000 0000000000
 8  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000010000 0200030000 0000000000
10  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000100 0010000302 0000000000 0000000000
12  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010000 0002030000 0000000000 0000000000
14  0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0001000020 0003000000 0000000000 0000000000
16  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0000200000 0030000000 0000000000 0000000000
18  0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 0020003000 0000000000 0000000000 0000000000
20  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 0200030000 0000000000 0000000000 0000000000
22  0000000000 0000000001 0000100001 0000100001 0000100001 0000100000 2000300000 0000000000 0000000000 0000000000
 3  6
SP WEP  XP
 4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100000 0200000003
 6  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0010000100 0020000300 0000000000
 8  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000010 0001000030 0200000000 0000000000
10  0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000320000 0000000000 0000000000
12  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0010000002 0030000000 0000000000 0000000000
14  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000020000 3000000000 0000000000 0000000000
 6  8
CP AUP MOP BIP RAP PDP
 6  0000000000 0000000000 0000000000 0010000000 0001000010 0001000010 0001000010 0003020000 0000000000 0000000000
 8  0000000000 0000000000 0000000100 0000001000 0100001000 0100001000 0100003000 0200000000 0000000000 0000000000
10  0000000000 0000000000 0000100000 0010000100 0010000100 0010000100 0030000100 0200000000 0000000000 0000000000
12  0000000000 0000000000 0010000001 0000100001 0000100001 0000100003 0000100020 0000000000 0000000000 0000000000
14  0000000000 0000000000 1000001000 0100001000 0100001000 0100003000 0000200000 0000000000 0000000000 0000000000
16  0000000000 0000000001 0000010000 1000010000 1000010000 1000030000 0200000000 0000000000 0000000000 0000000000
18  0000000000 0000000010 0001000010 0001000010 0001000010 0001000030 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000100 0010000100 0010000100 0010000100 0010000300 0000000000 0000000000 0000000000 0000000000
 3  6
LP MAP SLP
 4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100003 0000200000 0000000000
 6  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000000200 3000000000 0000000000
 8  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010000 3200000000 0000000000 0000000000
10  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0030000100 0200000000 0000000000 0000000000
12  0000000000 0000000000 1000010000 1000010000 1000010000 1000030000 1000002000 0000000000 0000000000 0000000000
```

(Continued)

```
14  0000000000 0000000010 0001000010 0001000010 0001000010 0001000030 0200000000 0000000000 0000000000 0000000000
 1  5
EL
 4  0000000000 0000000000 0000000000 0100001000 0100001000 0100001000 0300000002 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 3000020000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0100001000 0100001000 0100001000 0100003000 0002000000 0000000000 0000000000 0000000000
10  0000000000 0000000001 0000100001 0000100001 0000100003 0000100020 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000100 0010000100 0010000100 0010000300 0000200000 0000000000 0000000000 0000000000 0000000000
 2  6
JL  HL
 4  0000000000 0000000000 0000010000 0000100001 0000100001 0000100001 0000300000 2000000000 0000000000 0000000000
 6  0000000000 0000000000 0100000010 0001000010 0001000010 0003000010 0000020000 0000000000 0000000000 0000000000
 8  0000000000 0000000010 0000100001 0000100001 0000100003 0000100001 0000020000 0000000000 0000000000 0000000000
10  0000000000 0000001000 0010000100 0010000100 0030000100 0010000100 0020000000 0000000000 0000000000 0000000000
12  0000000000 0000100001 0000100001 0000100001 0000300001 0000100020 0000000000 0000000000 0000000000 0000000000
14  0000000000 0001000010 0001000010 0001000010 0003000010 0000020000 0000000000 0000000000 0000000000 0000000000
 1  9
DF
 8  0000000000 0000000000 0000000100 0000010000 1000010000 1000010000 1000010000 3002000000 0000000000 0000000000
10  0000000000 0000000000 0000100000 0100001000 0100001000 0100001000 0100003002 0000000000 0000000000 0000000000
12  0000000000 0000000000 0010000001 0000100001 0000100001 0000100003 0000200000 0000000000 0000000000 0000000000
14  0000000000 0000000000 1000001000 0100001000 0100001000 0100003002 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000010 0000100001 0000100001 0000100001 0000400020 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000100 0001000010 0001000010 0001000010 0003002000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000001000 0100001000 0100001000 0100001000 0100023000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000001000 0100001000 0100001000 0100001000 0400020000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000010000 1000010000 1000010000 1000010000 4000200000 0000000000 0000000000 0000000000 0000000000
 1  7
WH
12  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000100 0000020300 0000000000 0000000000
14  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010002 0000030000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0000200000 0003000000 0000000000 0000000000
18  0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 0200003000 0000000000 0000000000 0000000000
20  0000000000 0000000000 1000010000 1000010000 1000010000 1000000200 3000000000 0000000000 0000000000 0000000000
22  0000000000 0000000001 0000100001 0000100001 0000100001 0000002003 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000010 0001000010 0001000010 0001000010 0003020000 0000000000 0000000000 0000000000 0000000000
 4  7
RC  LC LEC JCR
12  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000320000 0000000000 0000000000
14  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000100 0030000000 0000000000 0000000000
16  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010002 3000000000 0000000000 0000000000
18  0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0000002030 0000000000 0000000000 0000000000
20  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0032000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 2300000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 1000010000 1000010000 1000010000 1000000200 3000000000 0000000000 0000000000 0000000000
 3  10
GF  RSQ WSQ
12  0000000000 0000000000 0000001000 0100001000 0100001000 0100001000 0300002000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000100001 0000100001 0000100001 0000100004 0002000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000010 0001000030 2000000000 0000000000 0000000000 0000000000
```

(Continued)

```
18   0000000000 0000000000 0010000100 0010000100 0010000100 0010000320 0000000000 0000000000 0000000000 0000000000
20   0000000000 0000000000 0100001000 0100001000 0100001000 0100003000 0000000000 0000000000 0000000000 0000000000
22   0000000000 0000000000 1000010000 1000010000 1000010000 1000032000 0000000000 0000000000 0000000000 0000000000
24   0000000000 0000000000 1000010000 1000010000 1000010000 3000020000 0000000000 0000000000 0000000000 0000000000
26   0000000000 0000000001 0000100001 0000100001 0000100003 0000020000 0000000000 0000000000 0000000000 0000000000
28   0000000000 0000000001 0000100001 0000100001 0000100003 0000200000 0000000000 0000000000 0000000000 0000000000
30   0000000000 0000000010 0001000010 0001000010 0001000030 0000200000 0000000000 0000000000 0000000000 0000000000
 3   7
NF ESF  XF
10   0000000000 0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0020000030 0000000000 0000000000
12   0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 0002000000 3000000000 0000000000
14   0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000010 0023000000 0000000000 0000000000
16   0000000000 0000000000 0000001000 0100001000 0100001000 0100001000 0100000020 0300000000 0000000000 0000000000
18   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000020003 0000000000 0000000000 0000000000
20   0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0020000300 0000000000 0000000000 0000000000
22   0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 2000003000 0000000000 0000000000 0000000000
 3   3
OK POK SOK
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000000003
 6   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000300000 0000000000
 8   0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000300000 0000000000 0000000000
12   4
BE ROC  SC  LI CLI SLI LLI  EM EEM WEM SEM HBM
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001
 6   0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002
 8   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000300000
10   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000300000 0000000000
10   4
SY NOM  AH  BI HCH  AR CAR GAR  XB  MB
 4   0000000000 0000000001 0000100001 0000100001 0000100001 0000300000 0000000000 0000000000 0000000000 0000000000
 6   0000000000 0000000001 0000100001 0000100001 0000300001 0000200000 0000000000 0000000000 0000000000 0000000000
 8   0000000000 0000100001 0000100001 0000100001 0000300002 0000000000 0000000000 0000000000 0000000000 0000000000
10   0000000000 0000100001 0000100001 0000100001 0000300002 0000000000 0000000000 0000000000 0000000000 0000000000
 2   5
OBN PRN
10   0000000000 0000000100 0010000100 0010000100 0010000300 0020000000 0000000000 0000000000 0000000000 0000000000
12   0000000000 0000010000 1000010000 1000010000 3000020000 0000000000 0000000000 0000000000 0000000000 0000000000
14   0000000000 0001000010 0001000010 0003000020 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
16   0000000000 0010000100 0010000300 0010000200 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
18   0000000000 0100001000 0100003000 0100002000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
```

Key Note: Each value represents one time unit (i.e. 1 year).
0 = no activity, 1 = year of thinning, 2 = year of felling,
3 = year of maximum mean annual increment, 4 = when 2 and 3 coincide.

Coded format for timber production under the extended rotation by 15 years thinning regime

```
16
 3 10
SS WSS QSS     0010000100 0010000100 0010000100 0010000100 0030000000 2000000000 0000000000
 6  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0030000000 2000000000 0000000000
 8  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000030 0000002000 0000000000 0000000000
10  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000030000 1000020000 0000000000 0000000000
12  0000000000 0000000000 0001000010 0001000010 0001000010 0001000030 0001000010 0020000000 0000000000 0000000000
14  0000000000 0000000000 0100001000 0100001000 0100001000 0100003000 0100000020 0000000000 0000000000 0000000000
16  0000000000 0000000000 1000010000 1000010000 1000010000 1000030000 1000020000 0000000000 0000000000 0000000000
18  0000000000 0000000001 0000100001 0000100001 0000100001 0000300000 0020000000 0000000000 0000000000 0000000000
20  0000000000 0000000010 0001000010 0001000010 0001000030 0001000000 2000000000 0000000000 0000000000 0000000000
22  0000000000 0000000100 0010000100 0010000100 0010000300 0010000002 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000100 0010000100 0010000100 0010000300 0010000020 0000000000 0000000000 0000000000 0000000000
 4  9
NS OMS  XS  MC
 6  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000300000 2000000000
 8  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000010000 1000032000 0000000000
10  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000100 0010000300 0000200000 0000000000
12  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010000 1000030020 0000000000 0000000000
14  0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0001000010 0003000000 0000000000 0000000000
16  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0010000002 0030000000 0000000000 0000000000
18  0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 0100003200 0000000000 0000000000 0000000000
20  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000032000 0000000000 0000000000 0000000000
22  0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000320000 0000000000 0000000000 0000000000
 3  6
SP WEP  XP
 4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000002003
 6  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0010000100 0010000300 0000000000
 8  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000010 0001000030 0000002000 0000000000
10  0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000300000 2000000000 0000000000
12  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0010000100 0030200000 0000000000 0000000000
14  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000010000 3000000000 0000000000 0000000000
 6  8
CP AUP MOP BIP RAP PDP
 6  0000000000 0000000000 0000000000 0010000000 0001000010 0001000010 0001000010 0003000000 2000000000 0000000000
 8  0000000000 0000000000 0000000100 0000001000 0100001000 0100001000 0100003000 0100002000 0000000000 0000000000
10  0000000000 0000000000 0000100000 0010000100 0010000100 0010000100 0030000100 0010002000 0000000000 0000000000
12  0000000000 0000000000 0010000001 0000100001 0000100001 0000100003 0000100001 0002000000 0000000000 0000000000
14  0000000000 0000000000 1000001000 0100001000 0100001000 0100003000 0100000002 0000000000 0000000000 0000000000
16  0000000000 0000000001 0000010000 1000010000 1000010000 1000030000 1000002000 0000000000 0000000000 0000000000
18  0000000000 0000000010 0001000010 0001000010 0001000010 0001000030 0002000000 0000000000 0000000000 0000000000
20  0000000000 0000000100 0010000100 0010000100 0010000100 0010000300 0020000000 0000000000 0000000000 0000000000
 3  6
LP MAP SLP
 4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100003 0000000002 0000000000
 6  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000010000 3020000000 0000000000
 8  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010000 3000002000 0000000000 0000000000
10  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0030000100 0010002000 0000000000 0000000000
12  0000000000 0000000000 1000010000 1000010000 1000010000 1000030000 1000010000 0200000000 0000000000 0000000000
```

(Continued)

```
14  0000000000 0000000010 0001000010 0001000010 0001000010 0001000030 0000002000 0000000000 0000000000 0000000000
1   5
EL
4   0000000000 0000000000 0000000000 0100001000 0100001000 0100001000 0300001000 0000200000 0000000000 0000000000
6   0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 3000010000 2000000000 0000000000 0000000000
8   0000000000 0000000000 0100001000 0100001000 0100001000 0100003000 0100000020 0000000000 0000000000 0000000000
10  0000000000 0000000001 0000100001 0000100001 0000100003 0000100001 0002000000 0000000000 0000000000 0000000000
12  0000000000 0000000100 0010000100 0010000100 0010000300 0010000002 0000000000 0000000000 0000000000 0000000000
2   6
JL  HL
4   0000000000 0000000000 0000010000 0000100001 0000100001 0000100001 0000300001 0000020000 0000000000 0000000000
6   0000000000 0000000000 0100000010 0001000010 0001000010 0003000010 0001000000 2000000000 0000000000 0000000000
8   0000000000 0000000010 0000100001 0000100001 0000100003 0000100001 0000100000 2000000000 0000000000 0000000000
10  0000000000 0000001000 0010000100 0010000100 0030000100 0010000100 0010000200 0000000000 0000000000 0000000000
12  0000000000 0000100001 0000100001 0000100001 0000300001 0000100001 0002000000 0000000000 0000000000 0000000000
14  0000000000 0001000010 0001000010 0001000010 0003000010 0001000000 2000000000 0000000000 0000000000 0000000000
1   9
DF
8   0000000000 0000000000 0000000100 0000010000 1000010000 1000010000 1000010000 3000000020 0000000000 0000000000
10  0000000000 0000000000 0000100000 0100001000 0100001000 0100001000 0100003000 0000200000 0000000000 0000000000
12  0000000000 0000000000 0010000001 0000100001 0000100001 0000100003 0000100002 0000000000 0000000000 0000000000
14  0000000000 0000000000 1000001000 0100001000 0100001000 0100003000 0000200000 0000000000 0000000000 0000000000
16  0000000000 0000000010 0000100001 0000100001 0000100001 0000300001 0002000000 0000000000 0000000000 0000000000
18  0000000000 0000000100 0001000010 0001000010 0001000010 0003000000 0200000000 0000000000 0000000000 0000000000
20  0000000000 0000001000 0100001000 0100001000 0100001000 0100004000 2000000000 0000000000 0000000000 0000000000
22  0000000000 0000001000 0100001000 0100001000 0100001000 0300001000 2000000000 0000000000 0000000000 0000000000
24  0000000000 0000010000 1000010000 1000010000 1000010000 3000010002 0000000000 0000000000 0000000000 0000000000
1   7
WH
12  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000100 0010000300 2000000000 0000000000
14  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010000 1000230000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0001000002 0003000000 0000000000 0000000000
18  0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 0100003000 0000000000 0000000000 0000000000
20  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 3020000000 0000000000 0000000000 0000000000
22  0000000000 0000000001 0000100001 0000100001 0000100001 0000100003 0200000000 0000000000 0000000000 0000000000
24  0000000000 0000000010 0001000010 0001000010 0001000010 0003000000 2000000000 0000000000 0000000000 0000000000
4   7
RC  LC LEC JCR
12  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000300000 2000000000 0000000000
14  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000100 0030000200 0000000000 0000000000
16  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000010000 4000200000 0000000000 0000000000
18  0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0001000030 0200000000 0000000000 0000000000
20  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0030000020 0000000000 0000000000 0000000000
22  0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 0400020000 0000000000 0000000000 0000000000
24  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 3020000000 0000000000 0000000000 0000000000
3   10
GF  RSQ WSQ
12  0000000000 0000000000 0000001000 0100001000 0100001000 0100001000 0300001000 0200000000 0000000000 0000000000
14  0000000000 0000000000 0000100001 0000100001 0000100001 0000100003 0000100020 0000000000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000010 0001000030 0000020000 0000000000 0000000000 0000000000
```

(Continued)

```
18   0000000000 0000000000 0010000100 0010000100 0010000100 0010000300 0002000000 0000000000 0000000000 0000000000
20   0000000000 0000000000 0100001000 0100001000 0100001000 0100003000 0200000000 0000000000 0000000000 0000000000
22   0000000000 0000000000 1000010000 1000010000 1000010000 1000030000 0200000000 0000000000 0000000000 0000000000
24   0000000000 0000000000 1000010000 1000010000 1000010000 3000010000 2000000000 0000000000 0000000000 0000000000
26   0000000000 0000000001 0000100001 0000100001 0000100003 0000100000 2000000000 0000000000 0000000000 0000000000
28   0000000000 0000000001 0000100001 0000100001 0000100003 0000100002 0000000000 0000000000 0000000000 0000000000
30   0000000000 0000000010 0001000010 0001000010 0001000030 0001000002 0000000000 0000000000 0000000000 0000000000
 3   7
NF ESF  XF
10   0000000000 0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0001000230 0000000000 0000000000
12   0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000000020 3000000000 0000000000
14   0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000010 0004000200 0000000000 0000000000
16   0000000000 0000000000 0000001000 0100001000 0100001000 0100001000 0100001000 0302000000 0000000000 0000000000
18   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100003 2000000000 0000000000 0000000000
20   0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0010000300 0000000000 0000000000 0000000000
22   0000000000 0000000000 0100001000 0100001000 0100001000 0100001000 0100023000 0000000000 0000000000 0000000000
 3   3
OK POK SOK
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000200003
 6   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000300000 0000000000
 8   0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000300002 0000000000 0000000000
12   4
BE ROC   SC   LI CLI SLI LLI   EM EEM WEM SEM HBM
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001
 6   0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001
 8   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 00001Q0001 0000100001 0000300000
10   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000300002 0000000000
10   4
SY NOM   AH   BI HCH   AR CAR GAR   XB   MB
 4   0000000000 0000000001 0000100001 0000100001 0000100001 0000300002 0000000000 0000000000 0000000000 0000000000
 6   0000000000 0000000001 0000100001 0000100001 0000300001 0000100002 0000000000 0000000000 0000000000 0000000000
 8   0000000000 0000100001 0000100001 0000100001 0000300001 0000200000 0000000000 0000000000 0000000000 0000000000
10   0000000000 0000100001 0000100001 0000100001 0000300001 0000200000 0000000000 0000000000 0000000000 0000000000
 2   5
OBN PRN
10   0000000000 0000000100 0010000100 0010000100 0010000300 0000000200 0000000000 0000000000 0000000000 0000000000
12   0000000000 0000010000 1000010000 1000010000 3000010000 2000000000 0000000000 0000000000 0000000000 0000000000
14   0000000000 0001000010 0001000010 0003000010 0002000000 0000000000 0000000000 0000000000 0000000000 0000000000
16   0000000000 0010000100 0010000300 0010000100 0020000000 0000000000 0000000000 0000000000 0000000000 0000000000
18   0000000000 0100001000 0100003000 0100001000 0200000000 0000000000 0000000000 0000000000 0000000000 0000000000
```

Key Note: Each value represents one time unit (i.e. 1 year).
0 = no activity, 1 = year of thinning, 2 = year of felling,
3 = year of maximum mean annual increment, 4 = when 2 and 3 coincide.

Coded format for timber production timing under the extended rotation by 5 years thinning regime

```
16
 3 10
SS WSS QSS   0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000000 2030000000 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000000 2030000000 0000000000 0000000000
 8  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0000002030 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000040000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0001000010 0001000010 0001000010 0001000030 0020000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0100001000 0100001000 0100001000 0100003020 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 1000010000 1000010000 1000010000 1000040000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000001 0000100001 0000100001 0000100000 0020300000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000010 0001000010 0001000010 0001000030 2000000000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000100 0010000100 0010000100 0010000302 0000000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000100 0010000100 0010000100 0010000320 0000000000 0000000000 0000000000 0000000000 0000000000
 4  9
NS OMS  XS  MC
    0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100000 2000300000 0000000000
 6  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000002000 0000030000 0000000000
 8  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 1000002000 0000030000 0000000000
10  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000100 0000200300 0000000000 0000000000
12  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000000020 0000030000 0000000000 0000000000
14  0000000000 0000000000 0001000010 0001000010 0001000010 0001000010 0002000000 0003000000 0000000000 0000000000
16  0000000000 0000000000 0010000100 0010000100 0010000100 0010000002 0000000000 0030000000 0000000000 0000000000
18  0000000000 0000000000 0100001000 0100001000 0100001000 0100000200 0000003000 0000000000 0000000000 0000000000
20  0000000000 0000000000 1000010000 1000010000 1000010000 1000002000 0000030000 0000000000 0000000000 0000000000
22  0000000000 0000000001 0000100001 0000100001 0000100001 0000020000 0000300000 0000000000 0000000000 0000000000
 3  6
SP WEP  XP
    0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000002000 0000000003
 4  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0010000200 0000000300 0000000000
 6  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000010 0000002030 0000000000 0000000000
 8  0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100000 2000300000 0000000000 0000000000
10  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0000200000 0030000000 0000000000 0000000000
12  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 2000000000 3000000000 0000000000 0000000000
14  0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 2000000000 3000000000 0000000000 0000000000
 6  8
CP AUP MOP BIP RAP PDP
    0000000000 0000000000 0000000000 0010000000 0001000010 0001000010 0001000000 2003000000 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0010000000 0001000010 0001000010 0001000000 2003000000 0000000000 0000000000
 8  0000000000 0000000000 0000000100 0000001000 0100001000 0100001000 0100004000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000100000 0010000100 0010000100 0010000100 0030002000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0010000001 0000100001 0000100001 0000100003 0002000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 1000001000 0100001000 0100001000 0100003002 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000001 0000010000 1000010000 1000010000 1000032000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000010 0001000010 0001000010 0001000010 0002000030 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000100 0010000100 0010000100 0010000100 0020000300 0000000000 0000000000 0000000000 0000000000
 3  6
LP MAP SLP
    0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100004 0000000000 0000000000
 4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100004 0000000000 0000000000
 6  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 0020000000 3000000000 0000000000
 8  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000002000 3000000000 0000000000 0000000000
10  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0030002000 0000000000 0000000000 0000000000
12  0000000000 0000000000 1000010000 1000010000 1000010000 1000030000 0200000000 0000000000 0000000000 0000000000
```

(Continued)

```
14  0000000000 0000000010 0001000010 0001000010 0001000010 0000002030 0000000000 0000000000 0000000000 0000000000
 1  5
EL
 4  0000000000 0000000000 0000000000 0100001000 0100001000 0100001000 0300200000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 4000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0100001000 0100001000 0100001000 0100003020 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000001 0000100001 0000100001 0000100003 0002000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000100 0010000100 0010000100 0010000302 0000000000 0000000000 0000000000 0000000000 0000000000
 2  6
JL  HL
 4  0000000000 0000000000 0000010000 0000100001 0000100001 0000100001 0000320000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0100000010 0001000010 0001000010 0003000000 2000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000010 0000100001 0000100001 0000100003 0000100000 2000000000 0000000000 0000000000 0000000000
10  0000000000 0000001000 0010000100 0010000100 0030000100 0010000200 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000100001 0000100001 0000100001 0000300001 0002000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0001000010 0001000010 0001000010 0003000000 2000000000 0000000000 0000000000 0000000000 0000000000
 1  9
DF
 8  0000000000 0000000000 0000000100 0000010000 1000010000 1000010000 1000000020 3000000000 0000000000 0000000000
10  0000000000 0000000000 0000100000 0100001000 0100001000 0100001000 0000203000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0010000001 0000100001 0000100001 0000100004 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 1000001000 0100001000 0100001000 0000203000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000010 0000100001 0000100001 0000100001 0002300000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000100 0001000010 0001000010 0001000000 0203000000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000001000 0100001000 0100001000 0100001000 2000003000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000001000 0100001000 0100001000 0100001000 2300000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000010000 1000010000 1000010000 1000010002 3000000000 0000000000 0000000000 0000000000 0000000000
 1  7
WH
12  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000000 2000000300 0000000000 0000000000
14  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000200000 0000030000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000010 0001000002 0000000000 0003000000 0000000000 0000000000
18  0000000000 0000000000 0100001000 0100001000 0100001000 0100002000 0000003000 0000000000 0000000000 0000000000
20  0000000000 0000000000 1000010000 1000010000 1000010000 0020000000 3000000000 0000000000 0000000000 0000000000
22  0000000000 0000000001 0000100001 0000100001 0000100000 0200000003 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000010 0001000010 0001000010 0001000000 2003000000 0000000000 0000000000 0000000000 0000000000
 4  7
RC  LC LEC JCR
12  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100000 2000300000 0000000000 0000000000
14  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000200 0030000000 0000000000 0000000000
16  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 1000200000 3000000000 0000000000 0000000000
18  0000000000 0000000000 0001000010 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000 0000000000
20  0000000000 0000000000 0010000100 0010000100 0010000100 0010000020 0030000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0100001000 0100001000 0100001000 0100020000 0300000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 1000010000 1000010000 1000010000 0020000000 3000000000 0000000000 0000000000 0000000000
 3 10
GF RSQ WSQ
12  0000000000 0000000000 0000001000 0100001000 0100001000 0100001000 0400000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000100001 0000100001 0000100001 0000100023 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0001000010 0001000010 0001000010 0000020030 0000000000 0000000000 0000000000 0000000000
```

(Continued)

```
18   0000000000 0000000000 0010000100 0010000100 0010000100 0002000300 0000000000 0000000000 0000000000 0000000000
20   0000000000 0000000000 0100001000 0100001000 0100001000 0200003000 0000000000 0000000000 0000000000 0000000000
22   0000000000 0000000000 1000010000 1000010000 1000010000 0200030000 0000000000 0000000000 0000000000 0000000000
24   0000000000 0000000000 1000010000 1000010000 1000010000 4000000000 0000000000 0000000000 0000000000 0000000000
26   0000000000 0000000001 0000100001 0000100001 0000100003 2000000000 0000000000 0000000000 0000000000 0000000000
28   0000000000 0000000001 0000100001 0000100001 0000100004 0000000000 0000000000 0000000000 0000000000 0000000000
30   0000000000 0000000010 0001000010 0001000010 0001000032 0000000000 0000000000 0000000000 0000000000 0000000000
 3   7
NF ESF  XF
10   0000000000 0000000000 0000000000 0001000010 0001000010 0001000010 0001000200 0000000030 0000000000 0000000000
12   0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000000020 0000000000 3000000000 0000000000
14   0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000200 0003000000 0000000000 0000000000
16   0000000000 0000000000 0000001000 0100001000 0100001000 0100001000 0002000000 0300000000 0000000000 0000000000
18   0000000000 0000000000 0000100001 0000100001 0000100001 0000100000 2000000003 0000000000 0000000000 0000000000
20   0000000000 0000000000 0010000100 0010000100 0010000100 0010000200 0000000300 0000000000 0000000000 0000000000
22   0000000000 0000000000 0100001000 0100001000 0100001000 0100020000 0000003000 0000000000 0000000000 0000000000
 3   3
OK POK SOK
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000 0000000003
 6   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000 0000300000 0000000000
 8   0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100002 0000300000 0000000000 0000000000
12   4
BE ROC   SC   LI CLI SLI LLI   EM EEM WEM SEM HBM
 4   0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002
 6   0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000
 8   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000 0000300000
10   0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000300000 0000000000
10   4
SY NOM   AH   BI HCH   AR CAR GAR   XB   MB
 4   0000000000 0000000001 0000100001 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000 0000000000
 6   0000000000 0000000001 0000100001 0000100001 0000300002 0000000000 0000000000 0000000000 0000000000 0000000000
 8   0000000000 0000100001 0000100001 0000100001 0000400000 0000000000 0000000000 0000000000 0000000000 0000000000
10   0000000000 0000100001 0000100001 0000100001 0000400000 0000000000 0000000000 0000000000 0000000000 0000000000
 2   5
OBN PRN
10   0000000000 0000000100 0010000100 0010000100 0010000400 0000000000 0000000000 0000000000 0000000000 0000000000
12   0000000000 0000010000 1000010000 1000010000 4000000000 0000000000 0000000000 0000000000 0000000000 0000000000
14   0000000000 0001000010 0001000010 0004000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
16   0000000000 0010000100 0010000300 0020000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
18   0000000000 0100001000 0100003000 0200000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
```

Key Note: Each value represents one time unit (i.e. 1 year).
0 = no activity, 1 = year of thinning, 2 = year of felling,
3 = year of maximum mean annual increment, 4 = when 2 and 3 coincide.

Coded format for timber production timing under the marginal thinning regime

```
16
 3 10
 SS WSS QSS
  6  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0000020000 0030000000 0000000000 0000000000
  8  0000000000 0000000000 0000000010 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000 0000000000
 10  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 2000030000 0000000000 0000000000 0000000000
 12  0000000000 0000000000 0001000010 0001000010 0001000010 0001000230 0000000000 0000000000 0000000000 0000000000
 14  0000000000 0000000000 0100001000 0100001000 0100001000 0002003000 0000000000 0000000000 0000000000 0000000000
 16  0000000000 0000000000 1000010000 1000010000 1000010000 2000030000 0000000000 0000000000 0000000000 0000000000
 18  0000000000 0000000001 0000100001 0000100001 0000000200 0000300000 0000000000 0000000000 0000000000 0000000000
 20  0000000000 0000000010 0001000010 0001000010 0000020030 0000000000 0000000000 0000000000 0000000000 0000000000
 22  0000000000 0000000100 0010000100 0010000100 0000200300 0000000000 0000000000 0000000000 0000000000 0000000000
 24  0000000000 0000000100 0010000100 0010000100 0002000300 0000000000 0000000000 0000000000 0000000000 0000000000
  4  9
 NS OMS  XS  MC
  6  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000020000 0000300000 0000000000
  8  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000010000 0200000000 0000030000 0000000000
 10  0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0010000002 0000000300 0000000000 0000000000
 12  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 0002000000 0000030000 0000000000 0000000000
 14  0000000000 0000000000 0001000010 0001000010 0001000010 0001000020 0000000000 0003000000 0000000000 0000000000
 16  0000000000 0000000000 0010000100 0010000100 0010000100 0000200000 0000000000 0030000000 0000000000 0000000000
 18  0000000000 0000000000 0100001000 0100001000 0100001000 0020000000 0000003000 0000000000 0000000000 0000000000
 20  0000000000 0000000000 1000010000 1000010000 1000010000 0200000000 0000030000 0000000000 0000000000 0000000000
 22  0000000000 0000000001 0000100001 0000100001 0000100000 2000000000 0000300000 0000000000 0000000000 0000000000
  3  6
 SP WEP  XP
  4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100000 0200000000 0000000003
  6  0000000000 0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0020000000 0000000300 0000000000
  8  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000
 10  0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000020000 0000300000 0000000000 0000000000
 12  0000000000 0000000000 0010000100 0010000100 0010000100 0010000002 0000000000 0030000000 0000000000 0000000000
 14  0000000000 0000000000 1000010000 1000010000 1000010000 1000020000 0000000000 3000000000 0000000000 0000000000
  6  8
 CP AUP MOP BIP RAP PDP
  6  0000000000 0000000000 0000000000 0010000000 0001000010 0001000010 0000020000 0003000000 0000000000 0000000000
  8  0000000000 0000000000 0000000100 0000001000 0100001000 0100001000 0200003000 0000000000 0000000000 0000000000
 10  0000000000 0000000000 0000100000 0010000100 0010000100 0010000100 0230000000 0000000000 0000000000 0000000000
 12  0000000000 0000000000 0010000001 0000100001 0000100001 0000100023 0000000000 0000000000 0000000000 0000000000
 14  0000000000 0000000000 1000001000 0100001000 0100001000 0000203000 0000000000 0000000000 0000000000 0000000000
 16  0000000000 0000000001 0000010000 1000010000 1000010000 0200030000 0000000000 0000000000 0000000000 0000000000
 18  0000000000 0000000010 0001000010 0001000010 0001000020 0000000030 0000000000 0000000000 0000000000 0000000000
 20  0000000000 0000000100 0010000100 0010000100 0010000200 0000000300 0000000000 0000000000 0000000000 0000000000
  3  6
 LP MAP SLP
  4  0000000000 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000200003 0000000000 0000000000
  6  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 1000000200 0000000000 3000000000 0000000000
  8  0000000000 0000000000 0000010000 1000010000 1000010000 1000010000 0200000000 3000000000 0000000000 0000000000
 10  0000000000 0000000000 0010000100 0010000100 0010000100 0010000100 0230000000 0000000000 0000000000 0000000000
 12  0000000000 0000000000 1000010000 1000010000 1000010000 1000032000 0000000000 0000000000 0000000000 0000000000
```

(Continued)

```
14 0000000000 0000000010 0001000010 0001000010 0001000000 0200000030 0000000000 0000000000 0000000000 0000000000
 1 5
EL
 4 0000000000 0000000000 0000000000 0100001000 0100001000 0100000002 0300000000 0000000000 0000000000 0000000000
 6 0000000000 0000000000 0000010000 1000010000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000
 8 0000000000 0000000000 0100001000 0100001000 0100001000 0002003000 0000000000 0000000000 0000000000 0000000000
10 0000000000 0000000001 0000100001 0000100001 0000100023 0000000000 0000000000 0000000000 0000000000 0000000000
12 0000000000 0000000100 0010000100 0010000100 0000200300 0000000000 0000000000 0000000000 0000000000 0000000000
 2 6
JL HL
 4 0000000000 0000000000 0000010000 0000100001 0000100001 0000100000 2000300000 0000000000 0000000000 0000000000
 6 0000000000 0000000000 0100000010 0001000010 0001000010 0003020000 0000000000 0000000000 0000000000 0000000000
 8 0000000000 0000000010 0000100001 0000100001 0000100003 0000020000 0000000000 0000000000 0000000000 0000000000
10 0000000000 0000001000 0010000100 0010000100 0030000100 0020000000 0000000000 0000000000 0000000000 0000000000
12 0000000000 0000100001 0000100001 0000100001 0000300020 0000000000 0000000000 0000000000 0000000000 0000000000
14 0000000000 0001000010 0001000010 0001000010 0003020000 0000000000 0000000000 0000000000 0000000000 0000000000
 1 9
DF
 8 0000000000 0000000000 0000000100 0000010000 1000010000 1000010000 0002000000 3000000000 0000000000 0000000000
10 0000000000 0000000000 0000100000 0100001000 0100001000 0100000002 0000003000 0000000000 0000000000 0000000000
12 0000000000 0000000000 0010000001 0000100001 0000100001 0000200003 0000000000 0000000000 0000000000 0000000000
14 0000000000 0000000000 1000001000 0100001000 0100000002 0000003000 0000000000 0000000000 0000000000 0000000000
16 0000000000 0000000010 0000100001 0000100001 0000100020 0000300000 0000000000 0000000000 0000000000 0000000000
18 0000000000 0000000100 0001000010 0001000010 0000002000 0003000000 0000000000 0000000000 0000000000 0000000000
20 0000000000 0000001000 0100001000 0100001000 0100020000 0000003000 0000000000 0000000000 0000000000 0000000000
22 0000000000 0000001000 0100001000 0100001000 0100020000 0300000000 0000000000 0000000000 0000000000 0000000000
24 0000000000 0000010000 1000010000 1000010000 1000200000 3000000000 0000000000 0000000000 0000000000 0000000000
 1 7
WH
12 0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0000020000 0000000300 0000000000 0000000000
14 0000000000 0000000000 0000010000 1000010000 1000010000 1000010002 0000000000 0000030000 0000000000 0000000000
16 0000000000 0000000000 0001000010 0001000010 0001000010 0000200000 0000000000 0003000000 0000000000 0000000000
18 0000000000 0000000000 0100001000 0100001000 0100001000 0200000000 0000003000 0000000000 0000000000 0000000000
20 0000000000 0000000000 1000010000 1000010000 1000000200 0000000000 3000000000 0000000000 0000000000 0000000000
22 0000000000 0000000001 0000100001 0000100001 0000002000 0000000003 0000000000 0000000000 0000000000 0000000000
24 0000000000 0000000010 0001000010 0001000010 0000020000 0003000000 0000000000 0000000000 0000000000 0000000000
 4 7
RC LC LEC JCR
12 0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000020000 0000300000 0000000000 0000000000
14 0000000000 0000000000 0000000100 0010000100 0010000100 0010000100 0020000000 0030000000 0000000000 0000000000
16 0000000000 0000000000 0000010000 1000010000 1000010000 1000010002 0000000000 3000000000 0000000000 0000000000
18 0000000000 0000000000 0001000010 0001000010 0001000010 0000002000 0000000030 0000000000 0000000000 0000000000
20 0000000000 0000000000 0010000100 0010000100 0010000100 0002000000 0030000000 0000000000 0000000000 0000000000
22 0000000000 0000000000 0100001000 0100001000 0100001000 2000000000 0300000000 0000000000 0000000000 0000000000
24 0000000000 0000000000 1000010000 1000010000 1000000200 0000000000 3000000000 0000000000 0000000000 0000000000
 3 10
GF RSQ WSQ
12 0000000000 0000000000 0000001000 0100001000 0100001000 0100002000 0300000000 0000000000 0000000000 0000000000
14 0000000000 0000000000 0000100001 0000100001 0000100001 0002000003 0000000000 0000000000 0000000000 0000000000
16 0000000000 0000000000 0001000010 0001000010 0001000000 2000000030 0000000000 0000000000 0000000000 0000000000
```

(Continued)

```
18  0000000000 0000000000 0010000100 0010000100 0010000020 0000000300 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0100001000 0100001000 0100002000 0000003000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 1000010000 1000010000 1000002000 0000030000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 1000010000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000 0000000000
26  0000000000 00Q0000001 0000100001 0000100001 0000020003 0000000000 0000000000 0000000000 0000000000 0000000000
28  0000000000 0000000001 0000100001 0000100001 0000200003 0000000000 0000000000 0000000000 0000000000 0000000000
30  0000000000 0000000010 0001000010 0001000010 0000200030 0000000000 0000000000 0000000000 0000000000 0000000000
 3   7
NF ESF  XF
10  0000000000 0000000000 0000000000 0001000010 0001000010 0001000010 0020000000 0000000030 0000000000. 0000000000
12  0000000000 0000000000 0000000000 1000010000 1000010000 1000010000 0002000000 0000000000 3000000000 0000000000
14  0000000000 0000000000 0000000010 0001000010 0001000010 0001000010 0020000000 0003000000 0000000000 0000000000
16  0000000000 0000000000 0000001000 0100001000 0100001000 0100000020 0000000000 0300000000 0000000000 0000000000
18  0000000000 0000000000 0000100001 0000100001 0000100001 0000020000 0000000003 0000000000 0000000000 0000000000
20  0000000000 0000000000 0010000100 0010000100 0010000100 0020000000 0000000300 0000000000 0000000000 0000000000
22  0000000000 0000000000 0100001000 0100001000 0100001000 2000000000 0000003000 0000000000 0000000000 0000000000
 3   3
OK POK SOK
 4  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000000003
 6  0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000300000 0000000000
 8  0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000200000 0000300000 0000000000 0000000000
12   4
BE ROC   SC   LI  CLI SLI LLI   EM EEM WEM SEM HBM
 4  0000000000 0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000
 6  0000000000 0000000000 0000000001 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000
 8  0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000100002 0000000000 0000300000
10  0000000000 0000000000 0000100001 0000100001 0000100001 0000100001 0000100001 0000200000 0000300000 0000000000
10   4
SY NOM   AH   BI  HCH   AR CAR GAR   XB   MB
 4  0000000000 0000000001 0000100001 0000100001 0000200000 0000300000 0000000000 0000000000 0000000000 0000000000
 6  0000000000 0000000001 0000100001 0000100001 0000400000 0000000000 0000000000 0000000000 0000000000 0000000000
 8  0000000000 0000100001 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000100001 0000100001 0000100002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000
 2   5
OBN PRN
10  0000000000 0000000100 0010000100 0010000100 0020000300 0000000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000010000 1000010000 1000020000 3000000000 0000000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0001000010 0001000020 0003000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0010000100 0010000400 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0100001000 0100004000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
```

Key Note: Each value represents one time unit (i.e. 1 year).
0 = no activity, 1 = year of thinning, 2 = year of felling,
3 = year of maximum mean annual increment, 4 = when 2 and 3 coincide.

Coded format for timber production timing under the no thinning regime

```
16
  3 10
 SS WSS QSS
  6  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0200000300 0000000000 0000000000 0000000000
  8  0000000000 0000000000 0000000000 0000000000 0000000000 0000000200 0003000000 0000000000 0000000000 0000000000
 10  0000000000 0000000000 0000000000 0000000000 0000000000 0000040000 0000000000 0000000000 0000000000 0000000000
 12  0000000000 0000000000 0000000000 0000000000 0000000000 2003000000 0000000000 0000000000 0000000000 0000000000
 14  0000000000 0000000000 0000000000 0000000000 0000000002 0300000000 0000000000 0000000000 0000000000 0000000000
 16  0000000000 0000000000 0000000000 0000000000 0000000020 3000000000 0000000000 0000000000 0000000000 0000000000
 18  0000000000 0000000000 0000000000 0000000000 0000000203 0000000000 0000000000 0000000000 0000000000 0000000000
 20  0000000000 0000000000 0000000000 0000000000 0000020030 0000000000 0000000000 0000000000 0000000000 0000000000
 22  0000000000 0000000000 0000000000 0000000000 0002000300 0000000000 0000000000 0000000000 0000000000 0000000000
 24  0000000000 0000000000 0000000000 0000000000 0200000300 0000000000 0000000000 0000000000 0000000000 0000000000
  4  9
 NS OMS  XS  MC
  6  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0200000003 0000000000 0000000000
  8  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000020000 0000000000 3000000000 0000000000
 10  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 2000000300 0000000000 0000000000 0000000000
 12  0000000000 0000000000 0000000000 0000000000 0000000000 0000002000 0000030000 0000000000 0000000000 0000000000
 14  0000000000 0000000000 0000000000 0000000000 0000000000 0000200000 0003000000 0000000000 0000000000 0000000000
 16  0000000000 0000000000 0000000000 0000000000 0000000000 0002000000 0030000000 0000000000 0000000000 0000000000
 18  0000000000 0000000000 0000000000 0000000000 0000000000 0200003000 0000000000 0000000000 0000000000 0000000000
 20  0000000000 0000000000 0000000000 0000000000 0000000002 0000030000 0000000000 0000000000 0000000000 0000000000
 22  0000000000 0000000000 0000000000 0000000000 0000000200 0000300000 0000000000 0000000000 0000000000 0000000000
  3  6
 SP WEP  XP
  4  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 2000000003 0000000000
  6  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000002 0000000300 0000000000 0000000000
  8  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0002000000 0003000000 0000000000 0000000000
 10  0000000000 0000000000 0000000000 0000000000 0000000000 0000002000 0000300000 0000000000 0000000000 0000000000
 12  0000000000 0000000000 0000000000 0000000000 0000000000 0000020300 0000000000 0000000000 0000000000 0000000000
 14  0000000000 0000000000 0000000000 0000000000 0000000000 0002000000 0000000000 3000000000 0000000000 0000000000
  6  8
 CP AUP MOP BIP RAP PDP
  6  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0002000300 0000000000 0000000000 0000000000
  8  0000000000 0000000000 0000000000 0000000000 0000000000 0000000200 0030000000 0000000000 0000000000 0000000000
 10  0000000000 0000000000 0000000000 0000000000 0000000000 0002300000 0000000000 0000000000 0000000000 0000000000
 12  0000000000 0000000000 0000000000 0000000000 0000000002 0030000000 0000000000 0000000000 0000000000 0000000000
 14  0000000000 0000000000 0000000000 0000000000 0000032000 0000000000 0000000000 0000000000 0000000000 0000000000
 16  0000000000 0000000000 0000000000 0000000000 0000400000 0000000000 0000000000 0000000000 0000000000 0000000000
 18  0000000000 0000000000 0000000000 0000000000 0004000000 0000000000 0000000000 0000000000 0000000000 0000000000
 20  0000000000 0000000000 0000000000 0000000000 0032000000 0000000000 0000000000 0000000000 0000000000 0000000000
  3  6
 LP MAP SLP
  4  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000030000 0000020000 0000000000 0000000000
  6  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 2000030000 0000000000 0000000000 0000000000
  8  0000000000 0000000000 0000000000 0000000000 0000000000 0002030000 0000000000 0000000000 0000000000 0000000000
 10  0000000000 0000000000 0000000000 0000000000 0000000302 0000000000 0000000000 0000000000 0000000000 0000000000
 12  0000000000 0000000000 0000000000 0000000000 0000032000 0000000000 0000000000 0000000000 0000000000 0000000000
```

(Continued)

```
14  0000000000 0000000000 0000000000 0000000030 0002000000 0000000000 0000000000 0000000000 0000000000 0000000000
 2  6
JL  HL
 4  0000000000 0000000000 0000000000 0000000000 0000000000 0000030000 0200000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0000000000 0000003000 2000000000 0000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0000000030 0000002000 0000000000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000000 0000003000 0002000000 0000000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 0000300000 0200000000 0000000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0003000000 0200000000 0000000000 0000000000 0000000000 0000000000 0000000000
 1  9
DF
 8  0000000000 0000000000 0000000000 0000000000 0000000000 0000000320 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000000 0000000000 0000000000 0002000003 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 0000000000 0000000000 2030000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0000000000 0000000002 3000000000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 0000000000 0000000230 0000000000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000000 0000000000 0000020300 0000000000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000000 0000000000 0302000000 0000000000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000000000 0000000000 0400000000 0000000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000000000 0000000002 3000000000 0000000000 0000000000 0000000000 0000000000 0000000000
 1  5
EL
 4  0000000000 0000000000 0000000000 0000000000 0000000002 0300000000 0000000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0000000000 0000020000 3000000000 0000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0000000000 0002003000 0000000000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000000 0000000023 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 0000200300 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
 1  7
WH
12  0000000000 0000000000 0000000000 0000000000 0000000000 0000020000 0000000300 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0000000000 0000000002 0000000000 0000030000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 0000000000 0000200000 0000000000 0003000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000000 0000000000 0200000000 0000003000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000000 0000000200 0000000000 3000000000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000000000 0000002000 0000000003 0000000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000000000 0000020000 0003000000 0000000000 0000000000 0000000000 0000000000 0000000000
 4  7
RC  LC LEC JCR
12  0000000000 0000000000 0000000000 0000000000 0000000000 0000020000 0000300000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0000000000 0000000000 0020000000 0030000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 0000000000 0000000002 0000000000 3000000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000000 0000000000 0000002000 0000000030 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000000 0000000000 0002000000 0030000000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000000000 0000000000 2000000000 0300000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000000000 0000000200 0000000000 3000000000 0000000000 0000000000 0000000000 0000000000
 3 10
GF RSQ WSQ
12  0000000000 0000000000 0000000000 0000000000 0000002000 0300000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0000000000 0002000003 0000000000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 0000000000 2000000030 0000000000 0000000000 0000000000 0000000000 0000000000
```

(Continued)

```
18  0000000000 0000000000 0000000000 0000000020 0000000300 0000000000 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000000 0000002000 0000003000 0000000000 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000000000 0000002000 0000030000 0000000000 0000000000 0000000000 0000000000 0000000000
24  0000000000 0000000000 0000000000 0000020000 3000000000 0000000000 0000000000 0000000000 0000000000 0000000000
26  0000000000 0000000000 0000000000 0000020003 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
28  0000000000 0000000000 0000000000 0000200003 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
30  0000000000 0000000000 0000000000 0000200030 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
 3   7
NF ESF  XF
10  0000000000 0000000000 0000000000 0000000000 0000000000 0020000000 0000000030 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000000000 0000000000 0000000000 0002000000 0000000000 3000000000 0000000000 0000000000
14  0000000000 0000000000 0000000000 0000000000 0000000000 0020000000 0003000000 0000000000 0000000000 0000000000
16  0000000000 0000000000 0000000000 0000000000 0000000020 0000000000 0300000000 0000000000 0000000000 0000000000
18  0000000000 0000000000 0000000000 0000000000 0000020000 0000000003 0000000000 0000000000 0000000000 0000000000
20  0000000000 0000000000 0000000000 0000000000 0020000000 0000000300 0000000000 0000000000 0000000000 0000000000
22  0000000000 0000000000 0000000000 0000000000 2000000000 0000003000 0000000000 0000000000 0000000000 0000000000
 3   3
OK POK SOK
 4  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000002 0000000000 0000000003 0000000000
 6  0000000000 0000000000 0000000000 0000000000 0000000000 0000000002 0000000000 0000300000 0000000000 0000000000
 8  0000000000 0000000000 0000000000 0000000000 0000000000 0000200000 0000300000 0000000000 0000000000 0000000000
12   4
BE ROC   SC   LI CLI SLI LLI  EM EEM WEM SEM HBM
 4  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000200000 0000000000
 6  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000002 0000000000 0000300000
 8  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000002 0000000000 0000300000 0000000000
10  0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000200000 0000300000 0000000000 0000000000
10   4
SY NOM  AH  BI HCH  AR CAR GAR  XB  MB
 4  0000000000 0000000000 0000000000 0000200000 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000
 6  0000000000 0000000000 0000000000 0000400000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
 8  0000000000 0000000000 0000000002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
10  0000000000 0000000000 0000000002 0000300000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
 2   5
OBN PRN
10  0000000000 0000000000 0000000000 0020000300 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
12  0000000000 0000000000 0000020000 3000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
14  0000000000 0000000020 0003000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
16  0000000000 0000000400 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
18  0000000000 0000004000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000 0000000000
```

Key Note: Each value represents one time unit (i.e. 1 year).
0 = no activity, 1 = year of thinning, 2 = year of felling,
3 = year of maximum mean annual increment, 4 = when 2 and 3 coincide.

APPENDIX 2

Sample run of FORM_CFGENS_MAIN1S

SAMPLE RUN OF FORM_CFGENS_MAIN1S

```
Command:RUN FORMY_CFGENY_MAIN1S
This program simulates timber production,
forest dispersed recreation,forest water-based
recreation, red deer stalking, and the cost
associated with these production functions at
specified time intervals.  Timber is measured in
cubic metres of volume, recreation in visitor days
and deer stalking in shooting days.

Enter time step for each run:
Data:5
Enter number of iterations:
Data:6
Enter interest rate (Please use decimals):
Data:0.05
Enter name of tabular output file for iteration    1
Data:ADATA86
Enter name of graphic output file for iteration    1
Data:BDATA86
Do you want to save clear-felled areas to do
inter-unit transferals? (Y/N)

Data:N
Enter name of tabular output file for iteration    2
Data:ADATA91
Enter name of graphic output file for iteration    2
Data:BDATA91
Do you want to save clear-felled areas to do
inter-unit transferals? (Y/N)

Data:N
Enter name of tabular output file for iteration    3
Data:ADATA96
Enter name of graphic output file for iteration    3
Data:BDATA96
Do you want to save clear-felled areas to do
inter-unit transferals? (Y/N)

Data:N
Enter name of tabular output file for iteration    4
Data:ADATA01
Enter name of graphic output file for iteration    4
Data:BDATA01
Do you want to save clear-felled areas to do
inter-unit transferals? (Y/N)

Data:N
Enter name of tabular output file for iteration    5
Data:ADATA06
Enter name of graphic output file for iteration    5
```

```
Data:BDATA06
Do you want to save clear-felled areas to do
inter-unit transferals? (Y/N)

Data:N
Enter name of tabular output file for iteration    6
Data:ADATA11
Enter name of graphic output file for iteration    6
Data:BDATA11
Do you want to save clear-felled areas to do
inter-unit transferals? (Y/N)

Data:N
```

APPENDIX 3

Sample run of FORM_CFGENS_MAIN2S

SAMPLE RUN OF FORM_CFGENS_MAIN2S

```
Command:RUN FORMY_CFGENY_MAIN2S
This program simulates timber production
forest dispersed recreation, forest water-
based recreation, red deer stalking and
the cost associated with these production
functions at specified time intervals.  It allows
replanting and inter-unit land transferals.
Timber is measured in cubic meters of volume,
recreation in visitor days and red deer stalking
in shooting days.

 Enter time step for each run:
Data:5
 Enter number of iterations:
Data:1
 Enter interest rate (Please use decimals):
Data:0.05
Enter name of clear-felled area data file:
Data:CLF86
Areas eligible for transferals are:

(1)SPRUCES                                   8.50ha
(2)SPRUCES/LARCHES/PINES                   134.70ha
(3)MIXED CONIFERS                           54.00ha
(4)CONIFERS/BROADLEAVES                      0.00ha
 Enter unit number of transferal from:
Data:2
 Enter unit number of transferal into:
Data:4
Current subcompartments in unit 2 are:
CMP SCOM COM SP YC    AREA
1030   A   2  SS 18     1.00
1030   E   2  SS 18     0.50
1058   B   2  SS 14     1.50
1058   B   3  SS 14     0.50
1063   B   1  SS 14     3.50
1065   A   1  SS 14     5.50
1068   B   1  SS 14     5.50
1070   B   1  SS 14     2.50
1073   C   1  SS 14     1.50
1075   B   1  SS 14     4.00
1061   D   3  NS 16     0.50
1068   A   1  NS 20     2.50
1008   A   1  EL 10     8.00
1012   A   1  EL 10     5.50
1013   B   1  EL 10     5.50
Do you want a transferal from any of these
compartments? (Y/N)

Data:Y
```

```
Enter compartment:
Data:1030
Enter subcompartment:
(Value should follow a space!)

Data: A
Enter component number:
(Value should follow a space!)

Data: 2
Enter new species (H = HELP):
(If coded value consists of less than three letters,
 then it should follow a space!)

Data:H
LIST OF SPECIES NAMES OF                          RANGE OF
CONIFERS/BROADLEAVES   UNIT                   YIELD CLASSES


SS WSS QSS                                              6-24
NS OMS  XS                                              6-22
SP WEP  XP                                              4-14
CP AUP MOP BIP RAP PDP                                  6-20
LP MAP SLP                                              4-14
JL  HL                                                  4-14
EL                                                      4-12
MC                                                      6-22
DF                                                      8-24
WH                                                     12-24
RC  LC LEC JCR                                         12-24
GF RSQ WSQ                                             12-30
NF ESF  XF                                             10-22
OK POK SOK                                              4-8
BE ROC  SC  LI CLI SLI LLI  EM EEM WEM SEM HBM          4-10
SY NOM  AH  BI HCH  AR CAR GAR  XB  MB                  4-12
BN PRN                                                 10-18
Enter new species (H = HELP):
(If coded value consists of less than three letters,
 then it should follow a space!)

Data: OK
Enter yield class:
(If value consists of one digit, then
 it should follow a space!)

Data: 6
 Another transferal?
Data:Y
Current subcompartments in unit 2 are:
CMP SCOM COM SP YC   AREA
1030  A  2  SS 18     1.00
1030  E  2  SS 18     0.50
1058  B  2  SS 14     1.50
```

```
1058   B   3   SS  14      0.50
1063   B   1   SS  14      3.50
1065   A   1   SS  14      5.50
1068   B   1   SS  14      5.50
1070   B   1   SS  14      2.50
1073   C   1   SS  14      1.50
1075   B   1   SS  14      4.00
1061   D   3   NS  16      0.50
1068   A   1   NS  20      2.50
1008   A   1   EL  10      8.00
1012   A   1   EL  10      5.50
1013   B   1   EL  10      5.50
Do you want a transferal from any of these
compartments? (Y/N)

Data:Y
 Enter compartment:
Data:1073
Enter subcompartment:
(Value should follow a space!)

Data: C
Enter component number:
(Value should follow a space!)

Data: 1
Enter new species (H = HELP):
(If coded value consists of less than three letters,
 then it should follow a space!)

Data: OK
Enter yield class:
(If value consists of one digit, then
 it should follow a space!)

Data: 4
 Another transferal?
Data:Y
Current subcompartments in unit 2 are:
CMP SCOM COM SP YC    AREA
1030   A   2   SS 18      1.00
1030   E   2   SS 18      0.50
1058   B   2   SS 14      1.50
1058   B   3   SS 14      0.50
1063   B   1   SS 14      3.50
1065   A   1   SS 14      5.50
1068   B   1   SS 14      5.50
1070   B   1   SS 14      2.50
1073   C   1   SS 14      1.50
1075   B   1   SS 14      4.00
1061   D   3   NS 16      0.50
1068   A   1   NS 20      2.50
1008   A   1   EL 10      8.00
```

```
1012  A  1  EL 10      5.50
1013  B  1  EL 10      5.50
Do you want a transferal from any of these
compartments? (Y/N)

Data:Y
 Enter compartment:
Data:1061
Enter subcompartment:
(Value should follow a space!)

Data: D
Enter component number:
(Value should follow a space!)

Data: 3
Enter new species (H = HELP):
(If coded value consists of less than three letters,
 then it should follow a space!)

Data: BE
Enter yield class:
(If value consists of one digit, then
 it should follow a space!)

Data: 4
 Another transferal?
Data:N

Enter name of tabular output file for iteration   1
Data:DT86
Enter name of graphic output file for iteration   1
Data:GDT86
Do you want to save clear-felled areas to do
inter-unit transferals?

Data:Y
 Enter name of file:
Data:CF86
```

APPENDIX 4

Technical coefficients of production functions for the Queen Elizabeth Forest Park

Technical coefficients of production functions for the Queen Elizabeth Forest Park (1986)

LAND

1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
2.9785				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
7.6389				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
1.9268				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	0.0000	0.0000
0.4024				

BUDGET

28.8704	30.1032	29.7424	29.7424	29.7443
30.3711	16.5538	32.7107	39.1239	35.7402
35.7402	35.7184	38.8523	19.1590	38.2175
46.9883	46.3469	46.2006	50.4728	48.9315
23.3065	28.2465	32.4144	31.0762	31.0762
31.5386	31.0904	20.4805	0.0123	0.0012
200.0000				

NATURE CONSERVATION

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	1.0000	0.0000
0.2249				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
7.2992				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0235				

TIMBER

0.0122	0.0103	0.0080	0.0080	0.0080
0.0084	0.1359	0.0123	0.0110	0.0075
0.0075	0.0075	0.0086	0.0970	0.0131
0.0115	0.0087	0.0087	0.0098	0.0095
0.1100	0.0116	0.0125	0.0105	0.0105
0.0109	0.0105	0.0000	0.0000	0.0000
0.0000				

DISPERSED RECREATION

0.0052	0.0054	0.0057	0.0057	0.0057
0.0057	0.0000	0.0061	0.0070	0.0078
0.0078	0.0078	0.0078	0.0066	0.0081
0.0096	0.0096	0.0096	0.0094	0.0000
0.0003	0.0003	0.0003	0.0003	0.0003
0.0003	0.0000	0.0027	0.3537	0.0000
0.0000				

WATER-BASED RECREATION

0.0060	0.0064	0.0066	0.0066	0.0066
0.0066	0.0000	0.0081	0.0101	0.0119
0.0119	0.0119	0.0115	0.0000	0.0055
0.0068	0.0093	0.0092	0.0097	0.0090
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0037	0.0259
0.0000				

DEER HUNTING

0.0260	0.0260	0.0259	0.0259	0.0259
0.0260	0.0260	0.0254	0.0254	0.0256
0.0256	0.0256	0.0254	0.0255	0.0247
0.0247	0.0247	0.0247	0.0247	0.0247
0.0243	0.0234	0.0234	0.0234	0.0234
0.0234	0.0234	0.0234	0.1330	0.1990
0.0000				

Technical coefficients of production functions
for the Queen Elizabeth Forest Park (1991)

LAND

1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
2.9785				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
7.6389				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
1.9268				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	0.0000	0.0000
0.4024				

BUDGET

38.3966	39.1716	39.9939	39.9914	40.8650
40.4031	21.9654	50.1176	54.3842	52.7156
52.7156	57.1500	56.9460	28.3786	66.0491
75.3392	72.4714	66.8797	70.6030	75.5286
35.2052	32.4928	31.7253	30.5164	29.9638
29.8967	29.8786	18.9150	0.0157	0.0016
255.2553				

NATURE CONSERVATION

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	1.0000	0.0000
0.2249				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
7.2992				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0235				

TIMBER

0.0119	0.0098	0.0081	0.0081	0.0085
0.0086	0.1007	0.0116	0.0103	0.0073
0.0073	0.0083	0.0084	0.1225	0.0139
0.0126	0.0093	0.0083	0.0090	0.0102
0.1148	0.0132	0.0123	0.0108	0.0103
0.0103	0.0103	0.0904	0.0000	0.0000
0.0000				

DISPERSED RECREATION

0.0059	0.0063	0.0067	0.0067	0.0067
0.0067	0.0000	0.0070	0.0080	0.0104
0.0104	0.0105	0.0102	0.0000	0.0075
0.0089	0.0116	0.0116	0.0115	0.0108
0.0000	0.0008	0.0008	0.0008	0.0008
0.0008	0.0008	0.0000	0.0027	0.3537
0.0000				

WATER-BASED RECREATION

0.0071	0.0073	0.0076	0.0076	0.0076
0.0075	0.0000	0.0100	0.0114	0.0142
0.0142	0.0141	0.0123	0.0000	0.0074
0.0102	0.0227	0.0228	0.0202	0.0190
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0037	0.0259
0.0000				

DEER HUNTING

0.0212	0.0212	0.0211	0.0211	0.0211
0.0212	0.0213	0.0218	0.0218	0.0215
0.0215	0.0215	0.0218	0.0221	0.0217
0.0217	0.0209	0.0209	0.0215	0.0217
0.0215	0.0191	0.0191	0.0191	0.0191
0.0191	0.0191	0.0192	0.1330	0.1990
0.0000				

Technical coefficients of production functions for the Queen Elizabeth Forest Park (1996)

LAND

1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
2.9785				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
7.6389				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
1.9268				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	0.0000	0.0000
0.4024				

BUDGET

59.9687	61.3537	59.9316	58.7345	59.5989
66.3722	63.2752	74.5609	80.8928	80.4089
74.5078	80.6096	82.4713	45.2051	95.1668
100.0611	93.1799	95.6620	100.9989	96.6882
56.7259	42.1897	38.4201	36.5390	37.3842
36.5159	36.6505	52.2747	0.0201	0.0020
325.7764				

NATURE CONSERVATION

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	1.0000	0.0000
0.2249				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
7.2992				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0235				

TIMBER

0.0135	0.0116	0.0081	0.0078	0.0081
0.0096	0.1273	0.0121	0.0102	0.0079
0.0070	0.0079	0.0084	0.1120	0.0138
0.0117	0.0088	0.0090	0.0098	0.0098
0.1061	0.0136	0.0102	0.0108	0.0114
0.0108	0.0108	0.0971	0.0000	0.0000
0.0000				

DISPERSED RECREATION

0.0064	0.0069	0.0080	0.0080	0.0079
0.0080	0.0000	0.0074	0.0093	0.0138
0.0139	0.0135	0.0127	0.0000	0.0077
0.0090	0.0140	0.0146	0.0140	0.0117
0.0000	0.0017	0.0017	0.0017	0.0017
0.0017	0.0017	0.0000	0.0027	0.3537
0.0000				

WATER-BASED RECREATION

0.0084	0.0087	0.0098	0.0098	0.0096
0.0101	0.0000	0.0116	0.0125	0.0167
0.0168	0.0145	0.0132	0.0000	0.0097
0.0163	0.0224	0.0256	0.0206	0.0173
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0037	0.0259
0.0000				

DEER HUNTING

0.0177	0.0177	0.0175	0.0175	0.0175
0.0177	0.0184	0.0198	0.0198	0.0190
0.0189	0.0195	0.0198	0.0205	0.0204
0.0204	0.0192	0.0187	0.0199	0.0204
0.0206	0.0152	0.0152	0.0152	0.0152
0.0152	0.0152.	0.0159	0.1330	0.1990
0.0000				

Technical coefficients of production functions
for the Queen Elizabeth Forest Park (2001)

LAND

1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
2.9785				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
7.6389				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
1.9268				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	0.0000	0.0000
0.4024				

BUDGET

96.9442	108.1378	96.8728	96.6447	106.2445
122.8557	38.7503	109.9277	118.6628	110.2082
109.8164	113.7557	117.9553	82.0834	152.5877
150.4115	131.7836	121.4818	126.5932	144.7966
75.6158	68.1079	65.2753	56.6843	56.7137
56.8559	73.8096	33.9988	0.0256	0.0026
415.7810				

NATURE CONSERVATION

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	1.0000	0.0000
0.2249				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
7.2992				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0235				

TIMBER

0.0172	0.0146	0.0076	0.0075	0.0086
0.0107	0.1184	0.0119	0.0105	0.0074
0.0073	0.0078	0.0085	0.1112	0.0152
0.0130	0.0095	0.0084	0.0095	0.0116
0.1310	0.0219	0.0205	0.0084	0.0084
0.0084	0.0144	0.1266	0.0000	0.0000
0.0000				

DISPERSED RECREATION

0.0062	0.0072	0.0122	0.0122	0.0123
0.0119	0.0000	0.0082	0.0110	0.0214
0.0227	0.0202	0.0184	0.0000	0.0086
0.0111	0.0159	0.0175	0.0126	0.0132
0.0000	0.0016	0.0016	0.0017	0.0017
0.0017	0.0017	0.0000	0.0027	0.3537
0.0000				

WATER-BASED RECREATION

0.0064	0.0071	0.0103	0.0103	0.0108
0.0071	0.0000	0.0108	0.0113	0.0152
0.0170	0.0142	0.0115	0.0000	0.0145
0.0163	0.0257	0.0271	0.0220	0.0167
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0037	0.0259
0.0000				

DEER HUNTING

0.0159	0.0159	0.0150	0.0150	0.0152
0.0159	0.0177	0.0196	0.0196	0.0184
0.0179	0.0189	0.0196	0.0208	0.0206
0.0206	0.0190	0.0184	0.0199	0.0206
0.0212	0.0125	0.0125	0.0121	0.0121
0.0121	0.0125	0.0129	0.1330	0.1990
0.0000				

Technical coefficients of production functions for the Queen Elizabeth Forest Park (2006)

LAND

1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
2.9785				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
7.6389				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
1.9268				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	0.0000	0.0000
0.4024				

BUDGET

142.2977	178.3982	153.2167	140.5385	179.0521
185.3472	104.3206	167.7290	175.0737	150.9707
144.7082	157.4808	170.3537	111.0468	223.2191
214.2777	163.6528	166.5047	190.1655	213.0942
240.3214	89.0261	104.5726	106.4077	106.1886
130.0551	134.5606	67.1665	0.0327	0.0033
530.6519				

NATURE CONSERVATION

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	1.0000	0.0000
0.2249				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
7.2992				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0235				

TIMBER

0.0174	0.0138	0.0082	0.0073	0.0100
0.0106	0.1124	0.0131	0.0110	0.0076
0.0070	0.0082	0.0095	0.1101	0.0170
0.0151	0.0094	0.0092	0.0117	0.0142
0.1264	0.0289	0.0193	0.0079	0.0079
0.0109	0.0120	0.1381	0.0000	0.0000
0.0000				

DISPERSED RECREATION

0.0061	0.0094	0.0218	0.0213	0.0231
0.0210	0.0000	0.0094	0.0148	0.0315
0.0353	0.0266	0.0234	0.0000	0.0095
0.0112	0.0138	0.0171	0.0146	0.0136
0.0000	0.0014	0.0015	0.0024	0.0024
0.0024	0.0022	0.0000	0.0027	0.3537
0.0000				

WATER-BASED RECREATION

0.0055	0.0055	0.0127	0.0122	0.0080
0.0055	0.0000	0.0065	0.0066	0.0166
0.0187	0.0132	0.0069	0.0000	0.0129
0.0133	0.0229	0.0281	0.0175	0.0134
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0037	0.0259
0.0000				

DEER HUNTING

0.0154	0.0154	0.0137	0.0135	0.0143
0.0154	0.0164	0.0210	0.0210	0.0190
0.0186	0.0200	0.0210	0.0231	0.0221
0.0221	0.0203	0.0195	0.0213	0.0221
0.0224	0.0106	0.0106	0.0097	0.0097
0.0101	0.0106	0.0108	0.1330	0.1990
0.0000				

Technical coefficients of production functions
for the Queen Elizabeth Forest Park (2011)

LAND

1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
2.9785				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
7.6389				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
1.9268				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	0.0000	0.0000
0.4024				

BUDGET

231.0636	271.3089	240.8889	205.7849	247.0457
252.1931	84.4553	240.2796	240.2152	196.7139
185.9382	217.7441	230.4186	121.5958	249.4913
248.8110	245.3807	207.1089	281.3239	249.1457
216.1610	154.6187	213.6001	226.6595	193.3115
234.1399	250.9640	164.2988	0.0417	0.0042
677.2585				

NATURE CONSERVATION

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	1.0000	0.0000
0.2249				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	1.0000
7.2992				

0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	1.0000	1.0000	1.0000	1.0000
1.0000	1.0000	1.0000	1.0000	1.0000
1.0235				

TIMBER

0.0157	0.0137	0.0097	0.0078	0.0106
0.0115	0.1072	0.0138	0.0121	0.0082
0.0074	0.0096	0.0111	0.1003	0.0159
0.0143	0.0116	0.0091	0.0144	0.0134
0.1121	0.0298	0.0175	0.0091	0.0073
0.0097	0.0111	0.1425	0.0000	0.0000
0.0000				

DISPERSED RECREATION

0.0076	0.0142	0.0463	0.0553	0.0280
0.0196	0.0000	0.0101	0.0136	0.0230
0.0263	0.0205	0.0150	0.0000	0.0077
0.0093	0.0167	0.0167	0.0149	0.0114
0.0000	0.0014	0.0019	0.0123	0.0120
0.0092	0.0068	0.0000	0.0027	0.3537
0.0000				

WATER-BASED RECREATION

0.0055	0.0055	0.0090	0.0136	0.0062
0.0055	0.0000	0.0065	0.0067	0.0132
0.0162	0.0074	0.0070	0.0000	0.0098
0.0104	0.0175	0.0205	0.0143	0.0104
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0037	0.0259
0.0000				

DEER HUNTING

0.0158	0.0158	0.0136	0.0130	0.0147
0.0158	0.0162	0.0237	0.0237	0.0209
0.0200	0.0221	0.0237	0.0254	0.0255
0.0255	0.0225	0.0215	0.0236	0.0255
0.0268	0.0096	0.0096	0.0085	0.0081
0.0089	0.0096	0.0097	0.1330	0.1990
0.0000				

APPENDIX 5

Sample run of FORM_ MOP

SAMPLE RUN OF FORM_MOP

```
Command:RUN FORMY_MOPY_WEIVS
At this stage of the solution process you need
to generate a random set of weighting vectors which
will be used to sample the entire set of nondominated
solutions. A number of 100XK is recommended, where
K is the number of the objective functions of your
problem.

 Enter number of objective functions:
Data:4
 Enter number of random sets of weighting vectors:
Data:400
Enter the name of the file, which contains the
intervals where each vector has to be drawn.
Data:WBN_WBNO
 Enter name for output file:
Data:WEIVD
```

```
Command:RUN FORMY_MOPY_SIMTEST
At this stage of the solution process you need
to test the set of weighting vectors for
similarity.  A distance parameter d is used
to establish similarity. Vectors with gradation
distances less than d are discarded. The final
value of d is established by performing multiple
forward runs according to the desired size of the
filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.1639
     2     4  0.163900
     1  0.856831  0.136107  0.002496  0.004566
     2  0.184209  0.267153  0.002092  0.546547
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.08
```

```
9     4  0.080000
1  0.856831  0.136107  0.002496  0.004566
2  0.544693  0.131894  0.323156  0.000257
3  0.507189  0.026339  0.082585  0.383888
4  0.399593  0.554068  0.046340  0.000000
5  0.296279  0.257012  0.000503  0.446206
6  0.289863  0.000467  0.709082  0.000589
7  0.215091  0.774408  0.003198  0.007303
8  0.131446  0.002747  0.394370  0.471437
9  0.081196  0.872413  0.002153  0.044238
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.07
11     4  0.070000
 1  0.856831  0.136107  0.002496  0.004566
 2  0.574790  0.240914  0.000038  0.184259
 3  0.653738  0.000488  0.341769  0.004005
 4  0.461972  0.000027  0.000026  0.537974
 5  0.394963  0.579979  0.000149  0.024910
 6  0.394612  0.024616  0.580641  0.000131
 7  0.268738  0.000273  0.234902  0.496087
 8  0.240221  0.104664  0.636076  0.019039
 9  0.241393  0.703908  0.000133  0.054566
10  0.117467  0.034999  0.549859  0.297676
11  0.081196  0.872413  0.002153  0.044238
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.065
14     4  0.065000
 1  0.856831  0.136107  0.002496  0.004566
 2  0.727347  0.005284  0.002549  0.264820
 3  0.705913  0.000330  0.289554  0.004204
 4  0.584865  0.321276  0.001928  0.091931
 5  0.483561  0.033489  0.081190  0.401760
 6  0.476549  0.000110  0.520705  0.002636
```

```
     7  0.399593  0.554068  0.046340  0.000000
     8  0.296279  0.257012  0.000503  0.446206
     9  0.289863  0.000467  0.709082  0.000589
    10  0.247019  0.595095  0.152536  0.005349
    11  0.162964  0.001040  0.832662  0.003333
    12  0.131086  0.836223  0.024121  0.008570
    13  0.114347  0.000007  0.079694  0.805952
    14  0.065312  0.000610  0.934078  0.000001
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.067
    13      4  0.067000
     1  0.856831  0.136107  0.002496  0.004566
     2  0.713129  0.001410  0.273282  0.012180
     3  0.584865  0.321276  0.001928  0.091931
     4  0.475903  0.012355  0.045914  0.465829
     5  0.476549  0.000110  0.520705  0.002636
     6  0.399593  0.554068  0.046340  0.000000
     7  0.296279  0.257012  0.000503  0.446206
     8  0.289863  0.000467  0.709082  0.000589
     9  0.247019  0.595095  0.152536  0.005349
    10  0.162964  0.001040  0.832662  0.003333
    11  0.124276  0.870825  0.000967  0.003932
    12  0.114347  0.000007  0.079694  0.805952
    13  0.054441  0.144665  0.799986  0.000908
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.068
    11      4  0.068000
     1  0.856831  0.136107  0.002496  0.004566
     2  0.698041  0.000002  0.280583  0.021375
     3  0.522908  0.057708  0.068985  0.350400
     4  0.484283  0.425726  0.089602  0.000388
     5  0.476549  0.000110  0.520705  0.002636
     6  0.337131  0.276123  0.002039  0.384707
```

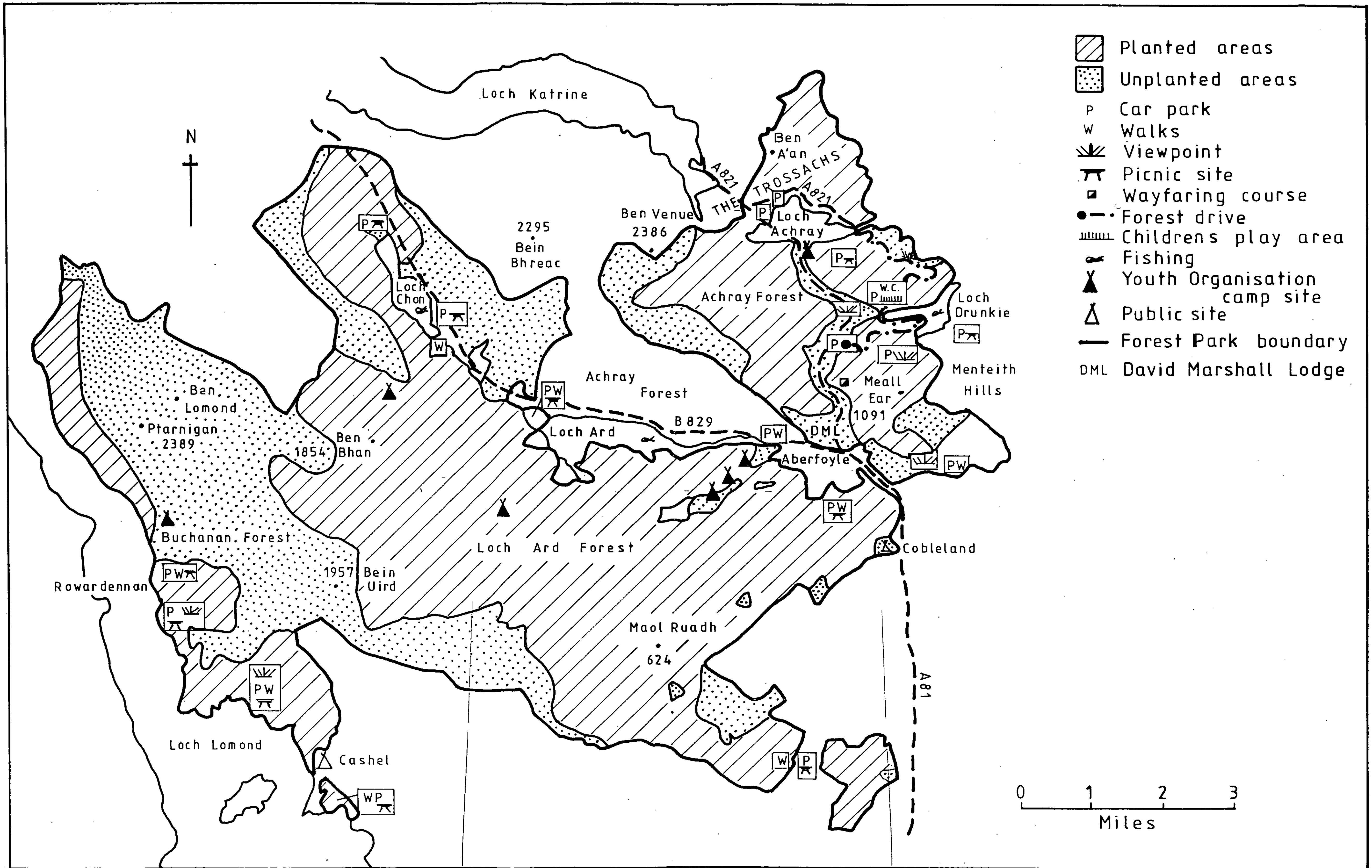
```
   7  0.289863  0.000467  0.709082  0.000589
   8  0.240354  0.749993  0.007425  0.002229
   9  0.184209  0.267153  0.002092  0.546547
  10  0.152245  0.026575  0.820493  0.000688
  11  0.081196  0.872413  0.002153  0.044238
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.0675
    13      4  0.067500
   1  0.856831  0.136107  0.002496  0.004566
   2  0.713129  0.001410  0.273282  0.012180
   3  0.584865  0.321276  0.001928  0.091931
   4  0.475903  0.012355  0.045914  0.465829
   5  0.476549  0.000110  0.520705  0.002636
   6  0.394963  0.579979  0.000149  0.024910
   7  0.296279  0.257012  0.000503  0.446206
   8  0.289863  0.000467  0.709082  0.000589
   9  0.247019  0.595095  0.152536  0.005349
  10  0.162964  0.001040  0.832662  0.003333
  11  0.124276  0.870825  0.000967  0.003932
  12  0.114347  0.000007  0.079694  0.805952
  13  0.054441  0.144665  0.799986  0.000908
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.0677
    13      4  0.067700
   1  0.856831  0.136107  0.002496  0.004566
   2  0.653611  0.006455  0.274342  0.065592
   3  0.584865  0.321276  0.001928  0.091931
   4  0.475903  0.012355  0.045914  0.465829
   5  0.394963  0.579979  0.000149  0.024910
   6  0.394612  0.024616  0.580641  0.000131
   7  0.296279  0.257012  0.000503  0.446206
   8  0.241393  0.703908  0.000133  0.054566
   9  0.240221  0.104664  0.636076  0.019039
```

```
   10  0.124276  0.870825  0.000967  0.003932
   11  0.123512  0.002120  0.868551  0.005817
   12  0.114347  0.000007  0.079694  0.805952
   13  0.028474  0.002072  0.968867  0.000587
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.0678
    13     4  0.067800
     1  0.856831  0.136107  0.002496  0.004566
     2  0.653611  0.006455  0.274342  0.065592
     3  0.584865  0.321276  0.001928  0.091931
     4  0.475903  0.012355  0.045914  0.465829
     5  0.394963  0.579979  0.000149  0.024910
     6  0.394612  0.024616  0.580641  0.000131
     7  0.296279  0.257012  0.000503  0.446206
     8  0.241393  0.703908  0.000133  0.054566
     9  0.240221  0.104664  0.636076  0.019039
    10  0.124276  0.870825  0.000967  0.003932
    11  0.123512  0.002120  0.868551  0.005817
    12  0.114347  0.000007  0.079694  0.805952
    13  0.028474  0.002072  0.968867  0.000587
Do you want to change distance? (Y/N)
Data:Y
Proceed with larger values of distance parameter,
if you want a smaller size filtered group or smaller
values of distance parameter, if you want a larger
size filtered group.

Enter name of file for the similarity test:
Data:WEIVD
Recommended value of distance parameter:  0.1639
 Enter value of distance parameter:
Data:0.0679
    12     4  0.067900
     1  0.856831  0.136107  0.002496  0.004566
     2  0.653611  0.006455  0.274342  0.065592
     3  0.584865  0.321276  0.001928  0.091931
     4  0.475903  0.012355  0.045914  0.465829
     5  0.394963  0.579979  0.000149  0.024910
     6  0.394612  0.024616  0.580641  0.000131
     7  0.296279  0.257012  0.000503  0.446206
     8  0.241393  0.703908  0.000133  0.054566
     9  0.240221  0.104664  0.636076  0.019039
    10  0.124276  0.870825  0.000967  0.003932
```

```
    11  0.117467  0.034999  0.549859  0.297676
    12  0.024513  0.035638  0.939380  0.000469
Do you want to change distance? (Y/N)
Data:N
Do you want to save the filtered vectors file?
Data:Y
 Please enter a name for the output file:
Data:FILTWV1



Command:RUN FORMY_MAGY_MAG1
This program is a matrix generator.  It prepares the
input deck for the first stage of the Tchebychev
minimization problem.

Enter number of objective functions:
Data:4
 Enter number of time periods:
Data:6
 Enter file name of ideal criterion vectors:
Data:IDEAL
 Enter name of filtered weighting vectors file:
Data:FILTWV1
Please enter the following information:
1.Character string identifying owner of data or
  address of owner(Use inverted commas).
2.Data number
3.Character string identifying nature of the problem.
(Use inverted commas).

Data:'QUEEN ELIZABETH FOREST PARK'
Data:1986
Data:'MINIMAX PROBLEM ONE (ITERATION 1)'
Do you want to transpose the matrix?(Y/N)
Data:N
Do you want to change the sign of all data values?(Y/N)
Data:N
Do you want to solve for the DUAL?(Y/N)
Data:N
 Enter identification number of the Tchebychev problem:
Data:1
 Enter name of input file:
Data:DATA
 Enter name of output file:
Data:TCB111
Do you have equality constraints?(Y/N)
Data:Y
 Enter total number of equality constraints:
Data:5
Enter their identification numbers. Please use
integers. For example 1,2,..e.t.c.(in ascending order)
```

```
Data:10 11 13 15 17
 Do you have inequality constraints of ">" type?(Y/N)
Data:Y
 Enter total number of ">" type inequality constraints:
Data:2
Enter their identification numbers.  Please use
integers.For example 1,2,..e.t.c.(in ascending order).

Data:8 9


Command:DEFINE 1,TCB111

Command:DEFINE 2,TCB11

Command:RUN FORMY_MOPY_MINLP

Command:RUN FORMY_INFACEY_INFA1
 Enter number of objective functions:
Data:4
 Enter number of time periods:
Data:6
 Enter input file name:
Data:TBR1_TB11
 Enter output file name:
Data:TB11A



Command:RUN FORMY_INFACEY_INFA2
 Enter number of objective functions:
Data:4
 Enter number of time periods:
Data:6
 Enter input file name:
Data:TB11A
 Enter output file name to be filtered:
Data:TB11B
 Enter output file name:
Data:TB11C
Enter string value of objective function 1
Data:TIMBER
Enter string value of objective function 2
Data:D.REC.
Enter string value of objective function 3
Data:W.REC.
Enter string value of objective function 4
Data:D.HUN.
 Enter solution number:
Data:3
 Enter graphics (mode 1) output file name:
Data:TB11D
 Enter graphics (mode 2) output file name:
```

```
Data:TB11E


Command:RUN FORMY_MOPY_WEVB
 Enter number of objective functions:
Data:4
 Enter name of criterion vectors file:
Data:STEST_STEST1
 Enter row number of preferred vector:
Data:3
 Enter value of convergence factor:
Data:0.6
 Enter number of current iteration:
Data:1
 Enter name for the LAMDA output file:
Data:LAMDA1
 Enter a name for the bounds output file:
Data:WBN1
```



Recreation Map of the Queen Elizabeth National Forest Park