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Different management regimes in a boreal forest landscape: ecological and economic effects

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Studia Forestalia Suecica
No. 208 · 2000

ISSN 0039-3150
ISBN 91-576-5981-8

Abstract

Fries, C. & Lämås, T. 2000. Different management regimes in a boreal forest landscape: ecological and economic effects. *Studia Forestalia Suecica 208.* 25 pp. ISSN 0039–3150. ISBN 91-576-5981-8.

Five management regimes were theoretically applied and evaluated in a 10 000 ha boreal forest landscape. Four regimes were designed to enhance conditions for biodiversity conservation, by establishing reserves and by modifying stand management. One regime was purely for timber production. Effects on biodiversity were assessed in terms of changes in population sizes within species or as number of species within ecological groups of the Red-listed species in the landscape. Assessments were based on the effects of management regimes on natural features of significance to animal and plant diversity. Effects on growing stock, harvest level, and economic return were assessed by means of the Forest Management Planning Package. Results indicate that biodiversity can be preserved only if the landscape is managed to satisfy the demands of species that require continuity in habitat conditions, and if management recognises fire-generated successions in boreal forest. Such management encompasses a system of patches managed so that important successional stages are always present in the landscape. The regime based on traditional silviculture did not encompass such features and, consequently, did not maintain biodiversity in the landscape. In the traditional silviculture regime, the future amount of deciduous trees was constant while the amount of old forest strongly decreased. As expected, this regime also generated the highest economic output. The decrease in harvested volumes and net incomes in the other regimes was approximately proportional to the reduction in non-protected, productive forest land.

Key words: conservation, ecological landscape planning, forest management planning, managed forests, natural forest dynamics, Sweden, trade-off analyses.

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MS. received 7 November 1998
Revised MS. accepted 9 December 1999

Introduction

By comparison with natural forests, features important to plant and animal diversity (composition, structures and processes) are lacking or have been altered in today's Swedish boreal forests (Linder & Östlund, 1992; Esseen, Ehnström, Ericson & Sjöberg, 1997). The number and quality of undisturbed forests, and the amounts of coarse woody debris and deciduous trees, have been heavily reduced. Fires are nowadays rare. In consequence, there is a general shortage of suitable habitats for specialised species and there are at present *ca.* 1100 endangered, vulnerable, rare, or care-demanding forest-dwelling animal and plant species on the Swedish Red Data list (Ehnström, Gärdenfors & Lindelöw, 1993; Ahlén & Tjernberg, 1996; Larsson, 1997; Hallingbäck, 1998; Aronsson, 1999; Thor & Arvidsson, 1999). Growing concern about ecological degradation, such as loss of productivity, extinction of species, *etc.*, has led to a search for management practices which can maintain biodiversity and ecosystem viability.

For stand level, modified silvicultural methods are now under development (*e.g.* Bradshaw, Gemmel & Björkman, 1994; Fries, Johansson, Pettersson & Simonsson, 1997). However, when the aim of forest management includes not only timber production but also maintenance of biodiversity, a larger scale must be considered. For this reason, the 'forest landscape' has been suggested as a suitable unit for forest management planning (Franklin, 1992, 1993; Liljelund, Pettersson & Zackrisson, 1992). A forest landscape may be *e.g.*, 5 000–25 000 ha in extent. One reason for choosing this larger scale is that the spatial arrangement of stands of different qualities determines what species may be present (*e.g.* Forman & Godron, 1986). The concept of using the landscape level in forestry emerged in the Pacific Northwest of the U.S.A. (*e.g.* Harris, 1984; Hansen, Spies, Swanson & Ohman, 1991; Hopwood, 1991; Franklin, 1992). This view soon reached Sweden; in the early 1990s, Swedish forestry companies began to develop 'ecological landscape plans' in certain project areas (Rülcker, Angelstam & Rosenberg, 1994; Törnquist, 1996; Angelstam & Pettersson, 1997; Fries, Carlsson, Dahlin, Lämås & Sallnäs, 1998). The primary aim of these plans was to improve conditions for conserving biodiversity, by means of networks of protected areas and modified management of the matrices. These plans concentrated on development of working methods which could be used in practice by the companies, rather than on analysis of different principles of managing a forest landscape and the outcomes of such management regimes.

A problem forest managers must consider, when planning the management of forest landscapes to conserve biodiversity, is finding a balance between modification of silvicultural methods, and establishment of permanent or temporary reserves. Another problem lies in forecasting the outcome of different management regimes. In the present study, we investigate these problems by theoretically applying five management regimes to a typical Swedish boreal forest landscape. In four of the regimes, timber production was restricted in various ways, to improve conditions for conserving biodiversity, *e.g.* by establishing reserves, by reducing harvest levels in certain areas or by general modification of stand management. The fifth regime was concerned exclusively with timber production.

The aim of the study was to estimate the effects of the different regimes on biodiversity, growing stock, harvest level, and economic return. Results from the study may be of help in choosing a strategy for combining timber production and maintenance of biodiversity in a forest of this type.

In the study, the Red-listed species found by an inventory of conservation values in the landscape, were used as a measure of biodiversity. Problems related to land ownership, *e.g.* how to implement the management regimes in the partly non-industrial, privately-owned area, were not addressed.

Material and Methods

The studied landscape

The landscape studied is situated in the middle boreal zone of northern Sweden (Ahti, Hämet-Ahti & Jalas, 1968), 60 km north-west of Umeå

(63°35′ N, 20°15′ E; Fig. 1). It has an area of *ca.* 10 000 ha. The eastern boundary is formed by the river Vindelälven (here 150–170 m a.s.l.). To the west of the river, the terrain consists of coarse, glacifluvial sediments, succeeded by undulating, hilly terrain, mainly covered by deep deposits of glacial till, with several peatlands in the valley bottoms (National Atlas of Sweden, 1994). The highest summit is 402 m a.s.l. Eighty-nine per cent of the landscape is productive forest land, 8% is peatland, while the remainder consists of lakes and agricultural land. Eight per cent of the productive forest land was classified as dry from an analysis of colour infrared aerial photographs, 63% as mesic, and 29% as moist or wet (Fig. 2*a*).

Large-scale logging began in the region about 1850, when large Scots pines (*Pinus sylvestris* L.) were felled to produce lumber for export (Östlund, 1993). As the pulp and paper industry developed at the end of the 19th century, even smaller pines and Norway spruce (*Picea abies* (L.) Karst.) became valuable. The clearfelling system was introduced into the landscape studied in the 1930s. Since about 1950, this has been the only silvicultural system of importance. The clearfelling system normally includes soil scarification, planting of pine, cleaning, and one or more thinnings before the rotation is concluded by clearfelling at a stand age of 100–120 years.

Today, pine, spruce and deciduous trees make up about 46%, 43% and 11%, respectively, of the standing volume in the landscape studied. About 46% of the productive forest land contains stands ≤50 years old, and 31% contains stands >100 years old (Fig. 2*b*). The youngest portion has, in most cases, been established by natural regeneration or planting after the first clearfelling. The mean standing volume in the landscape studied is *ca.* 104 m^3 ha^{-1}, and mean site productivity is 3.9 m^3 $ha^{-1}yr^{-1}$, which is close to the level in the coastal area of the county of Västerbotten (Anon., 1997). The volume of coarse woody debris has been reduced from a probable natural level of 40–80 m^3 ha^{-1}, to an average of 1.7 m^3 ha^{-1} (Lämås & Fries, 1995*a*). Forestry companies own 72% of the productive forest land; the remaining 28% consists of *ca.* 100 non-industrial private forest holdings. We consider the studied landscape to be representative of a large area of northern Sweden. Historic land use is, for example, similar to land use in a large proportion of the North-Swedish boreal forests (Östlund, 1993). The present age-class and tree-species distributions are similar to those in the two northernmost counties of Sweden (Anon., 1997).

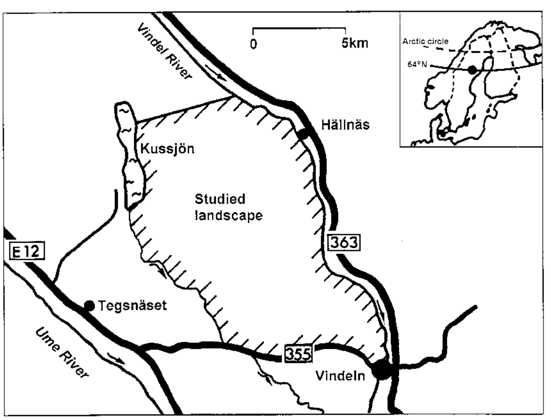


Fig. 1. Location of the studied landscape.

There are differences between the structure of the natural and the man-made landscape, as indicated by the soil moisture map (Fig. 2*a*) and the forest map (Fig. 2*b*), respectively. The shape of the patches formed by differences in soil moisture is more complex than the pattern formed by the stands on the forest map. Another characteristic is that many moist or wet areas have elongated and pointed shapes, indicating the presence of depressions or small streams, which are not found on the forest map. The relatively old forest is fragmented, and no large, continuous areas with stands >100 years old now remain. Consequently, about half a century of forestry according to the clearfelling system, has resulted in a considerable change in what may be assumed to have been the natural structure of the landscape studied.

Areas containing Red-listed species or with a high frequency of natural structures (multi-storey tree canopies, patchy distribution of tree species and tree stems, occurrence of large, old and dead trees, especially Scots pines and deciduous trees, *etc.*) – indicating that they have the potential to support Red-listed species – were located by interpretation of colour infrared aerial photographs, followed by a field inventory (Fig. 3) (Sporrong, unpubl. data). Their total area is 670 ha (7.8% of the productive forest land). The six areas with the highest conservation value (*i.e.* those which contain the most

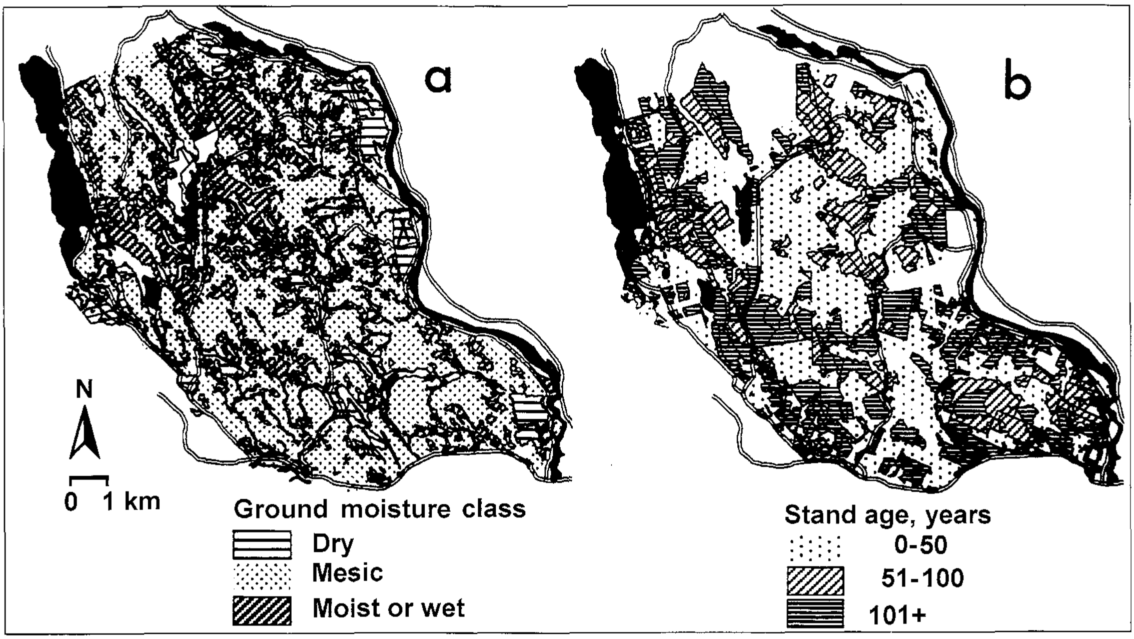


Fig. 2a–b. Soil moisture (a) and mean stand ages (grouped into three ageclasses), (b) in the studied landscape. Soil moisture is classified by interpretation of colour infrared aerial photographs (scale 1:20000) into dry, mesic, or moist or wet. ■ Lakes and rivers, main roads.

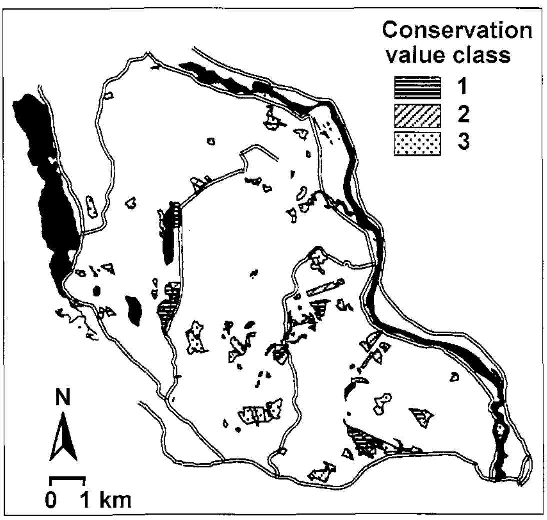


Fig. 3. Areas with high nature conservation values (class 1; highest value–127 ha; 1.5% of the productive forest land in the studied landscape), class 2 (194 ha; 2.2%), and class 3 (353 ha; 4.1%)). ■ Lakes and rivers, main roads.

'natural' stand structures and the majority of the Red-listed species in the landscape studied), consist of late-successional forests that appeared after fires about 150 years ago. Two of them also contain moist or wet sites dominated by Norway spruce forests regenerated by gap dynamics. The areas of highest value have in common the fact that no thinnings, or only light thinnings, have been carried out during the past 50 years.

Most of the 42 Red-listed species found in the studied landscape, are fungi which use dead wood as a substrate (mainly spruce logs) or lichens confined to old or dead conifers or deciduous trees (Table 1). Some of the species may survive cutting, others do not. Twelve Red-listed species, according to categories defined by IUCN (Groombridge, 1993), are considered to be endangered (3), vulnerable (6), or rare (3). Thirty species, according to categories defined by the Swedish Environmental Protection Agency, are considered care-demanding (Ehnström *et al.*, 1993; Ahlén & Tjernberg, 1996; Larsson, 1997; Hallingbäck, 1998; Aronsson, 1999; Thor & Arvidsson, 1999). Because bryophytes and invertebrates were not systematically examined by specialists, there are probably more Red-listed species in these groups in the studied landscape than are shown in Table 1. Also among vertebrates, there are Red-listed species that probably occasionally occur in the landscape, but which are not shown in the table.

Table 1. *Red-listed species found in the studied landscape, by preferred biotope and by important features, etc., on which they depend (Ehnström & Waldén, 1986; Ahlén & Tjernberg, 1996; Larsson, 1997; Hallingbäck, 1998; Aronsson, 1999; Thor & Arvidsson, 1999). Species nomenclature follows the Red-lists cited above*

Species	Organism group[a)]	Threat category	Preferred biotope	Features, etc.[b)]
Pytho abieticola	I, beetle	2	Spruce forest	Spruce logs (with bark)
Amylocystis lapponica	F	2	Spruce forest	Spruce logs
Cystostereum murraii	F	4	Spruce forest	Spruce (stumps or logs); moist microclimate
Fomitopsis rosea	F	4	Spruce forest	Spruce logs
Perenniporia subacida	F	2	Spruce forest	Spruce logs (wood); moist microclimate
Phellinus ferrugineofuscus	F	4	Spruce forest	Spruce logs (bark)
Phellinus nigrolimitatus	F	4	Spruce forest	Spruce logs
Phlebia centrifuga	F	4	Spruce forest	Spruce logs
Pseudographis pinicola	F	4	Spruce forest	Spruces (stem base with rough bark)
Bryoria nadvornikiana	L	4	Spruce forest	Spruce branches
Chaenotheca gracillima	L	4	Spruce forest	Spruce snags (wood); moist and shady conditions
Chaenothecopsis viridialba	L	4	Spruce forest	Spruce trunk (bark); moist site
Microcalicium ahlneri	L	4	Spruce forest	Spruce or pine (snag or trunk); moist site
Ramalina thrausta	L	1	Spruce forest	Old spruce, branches; moist microclimate
Anastrophyllum hellerianum	B	4	Spruce forest	Logs; moist microclimate
Lophozia ascendens	B	4	Spruce forest	Logs; moist microclimate
Epipogium aphyllum	Va	4	Spruce forest	Ground; moist
Ranunculus lapponicus	Va	4	Spruce forest	Ground; moist-wet
Agathidium discoideum	I, beetle	4	Deciduous/spruce forest	Large aspen logs
Melandrya barbata	I, beetle	1	Deciduous/spruce forest	Large aspen logs
Clavicorona pyxidata	F	4	Deciduous/spruce forest	Aspen logs
Haploporus odorus	F	4	Deciduous/spruce forest	Old goat willow (bark)
Calicium adaequatum	L	4	Deciduous/spruce forest	Alder branches; moist microclimate
Chaenotheca laevigata	L	2	Deciduous/spruce forest	Snags (wood)
Collema nigrescens	L	4	Deciduous/spruce forest	In boreal forest: Aspen (bark); moist microclimate
Collema curtisporum	L	1	Deciduous/spruce forest	Medium-aged aspen (bark)
Collema furfuraceum	L	2	Deciduous/spruce forest	Old aspen (bark)
Collema subnigrescens	L	4	Deciduous/spruce forest	Old aspen (bark); shady and moist microclimate
Ramalina sinensis	L	4	Deciduous/spruce forest	Old aspen or willow (bark)
Sclerophora coniophaea	L	4	Deciduous/spruce forest	Spruce, alder or birch (bark on trees or stumps)
Dryocopus martius	Ve, bird	4	Deciduous/spruce forest	Nest-holes in large aspen or pine
Picus canus	Ve, brid	3	Deciduous/spruce forest	Nest-holes in aspen
Cladonia parasitica	L	4	Pine forest	Pine logs (wood)
Ursus arctos	Ve, mammal	4	Forest land	
Picoides tridactylus	Ve, bird	4	Natural boreal forests	Nest-holes in several tree species
Tetrao urogallus	Ve, bird	4	Unfragmented forest	
Carex rhynchophysa	Va	3	Riparian zone	Ground, oxygen and nutrient rich
Margaretifera margaretifera	I, mussel	2	Stream	
Salmo trutta	Ve, fish	4	Stream	
Grus grus	Ve, bird	4	Mire	
Botrychium lanceolatum	Va	3	Meadow	Ground, dry and nutrient poor
Botrychium multifidum	Va	4	Meadow	Ground, dry and nutrient poor

[a)] B = Bryophyte, F = Fungi, I = Invertebrate, L = Lichen, Va = Vascular plant, Ve = Vertebrate.
[b)] Many Red-listed fungi seem to prefer large logs (Kruys, Fries, Jonsson, Lämås & Ståhl, 1999).

Management regimes

Different management regimes, aiming at different levels of timber production and maintenance of biodiversity, were applied to the landscape. Three main approaches were used: No Protected Areas (NPA), Protected Areas (PA), and a Landscape Planning approach (LP) (Table 2). Except for the NPA option, these approaches designate areas for certain silviculture regimes, *e.g.* reserves, prescribed burning, or extended rotations. Furthermore, areas outside such designated areas could be managed either for a Highest net present value of Timber Production approach (HTP), or a Modified Timber Production approach (MTP). The LP option, however, was combined only with the MTP approach. Thus five management regimes were applied to the landscape.

Highest Timber Production (HTP)

The HTP approach illustrates a single aim, commercial forestry aiming at the production of valuable timber. Silviculture was based on the clearfelling system, and regeneration measures generally consisted of soil scarification, planting or natural regeneration under seed trees. Cleaning, and one or more thinnings, aimed at improving conifers, were normally carried out during a rotation.

Modified Timber Production (MTP)

The MTP approach is based on important measures in Swedish boreal forests for enhancing biodiversity, *i.e.* increasing the number and quality of undisturbed forests, the amounts of coarse woody debris, the number of large and old deciduous trees, and reintroducing fire as an ecological process (Esseen *et al.*, 1997).

In particular, 5% of the productive forest land, in addition to reserves, was withdrawn from the calculation of potential cut to provide for the retention of small patches of forest, and for buffer or restoration zones. The aim of buffer zones is to reduce negative effects from the matrix on features and species in selected habitats (Baker, 1992; Murcia, 1995; Angelstam, 1997; Fries *et al.*, 1998). Their shape and management should therefore vary, depending on the situation. Restoration zones are established to support habitats valuable for conservation by enhancing processes characteristic of that particular habitat.

In thinning operations, the priority for cutting deciduous trees was lower in the MTP than in the HTP approach. At final harvest, 1% of the standing volume was left to represent retention of single green trees and the creation of snags at final harvest. Prescribed burning, which leads to increased regeneration costs and a natural regeneration mainly of deciduous trees, was implemented on 3% of productive forest land in the first 50-year period (corresponding to 5% of the final harvested area in the NPA approach).

The MTP approach also includes uneven-aged silviculture on a minor proportion of the moist spruce sites. However, in the planning system used (see 'Evaluation of effects on timber production' below), such silviculture was impossible to apply. Instead, the above 5% area set aside was assumed also to represent the possible reductions in timber production caused by uneven-aged silviculture.

Table 2. *The various components which form the management regimes. (PFL denotes productive forest land.)*

Regime	Protected area of PFL[a] %	Prescribed burning	Green tree retention	Priority for cutting deciduous trees at thinning	Small patches of forest left in final harvest	Buffer zones around selected streams	Management for continuity of successional biotopes
NPA + HTP	0	No	No	High	No	No	No
NPA + MTP	0	Yes[b]	Yes	Low	Yes	No	No
PA + HTP	2.5–25	No	No	High	No	No	No
PA + MTP	2.5–25	Yes[b]	Yes	Low	Yes	No	No
LP + MTP	4.1	Yes[c]	Yes	Low	Yes	Yes	Yes

[a] Apart from small patches left in cuttings, if any.
[b] 1% of standing volume left at final cutting prior to prescribed burning.
[c] 25% of standing volume left at final cutting prior to prescribed burning.

It is not possible to depict differences between the HTP and the MTP approaches on a small-scale map. However, one characteristic and fundamental difference between the HTP and the MTP approaches is that every landscape patch will in the long term be more homogeneous and have more distinct borders in the HTP than in the MTP approach (Fig. 4). Modification of the MTP approach, and the proportion of productive forest land withdrawn, are similar to those agreed upon in the Swedish FSC certification process (The Swedish FSC Working Group, 1997).

No Protected Areas (NPA)

In the NPA approach, no areas were established as reserves. The NPA approach was combined either with the HTP approach, forming the NPA + HTP regime, or with the MTP approach, forming the NPA + MTP regime.

Protected Areas (PA)

In the PA approach, areas were established from which no timber was removed. The approach was applied so that 2.5, 5, 15, and 25%, respectively, of the productive forest land in the study area was protected (hereafter referred to as PA2.5, PA5, *etc.*). The proportion 15% was included in our analyses because an expert group judged that this level is needed to maintain biodiversity in Swedish forests (Liljelund *et al.*, 1992; Lämås & Fries, 1995*b*). The line of action suggested by the group, established as official policy in 1993, was instead to reduce the proposed reserved proportion 'by more than half', and to modify management of the remainder of the forest land. This was the basis for our choice of the proportion 5%. The PA options were combined either with the HTP approach, forming the PA + HTP regimes, or with the MTP approach, forming the PA + MTP regimes.

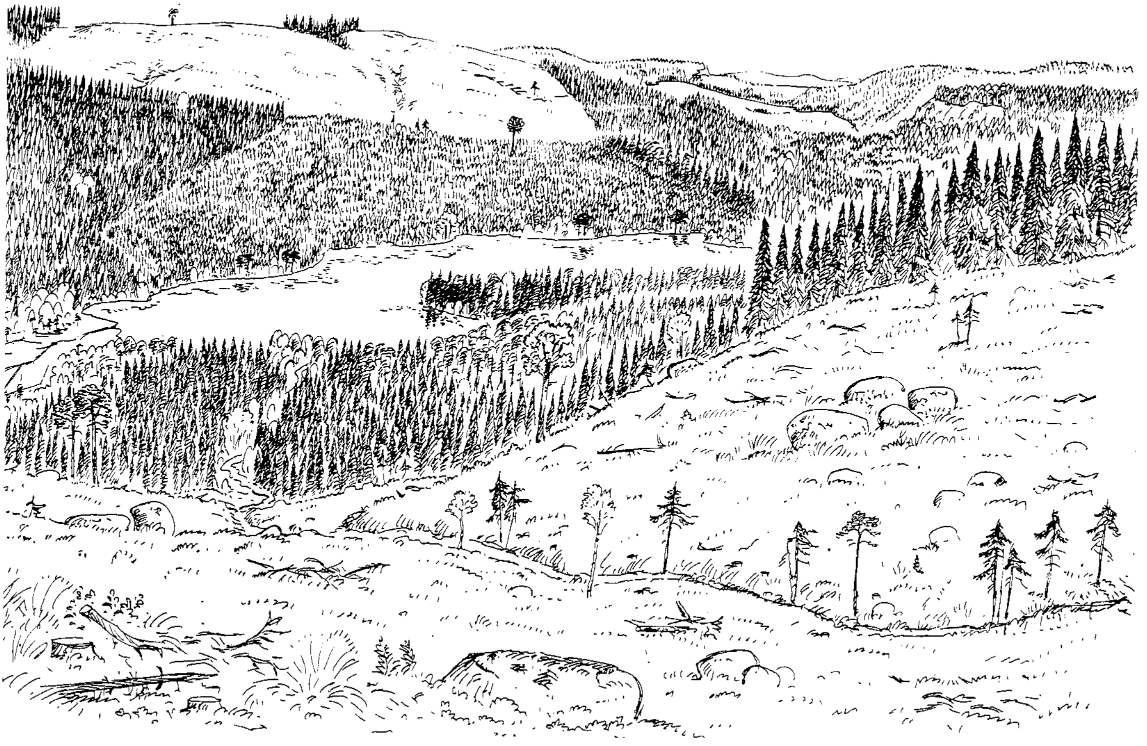
The procedure for establishing reserves was as follows: First, patches with the highest conservation value (conservation value class 1) were selected as reserves. Reserve areas were then chosen among the older portion of stands, especial attention being paid to conservation value class 2, with the ambition to protect most of the site types in the landscape. To reduce negative edge effects on the reserves, we attempted to reduce the perimeter : area ratios and to form relatively large reserve units. When a higher proportion of reserved area was established, connections between areas of high conservation value were made whenever possible. In the combination PA and MTP, small patches can be left adjacent to protected areas, as buffer zones or restoration zones.

The establishment of 2.5% (*ca.* 220 ha) of the productive forest land as reserves made it possible to preserve the six areas in conservation value class 1 and the 5.2 ha stand containing the endemic lichen *Cladonia parasitica* (Hoffm.) Hoffm., characteristic of the landscape. By preserving *ca.* 19 ha of dry sediment dominated by pine > 100 years old, an additional major forest type was included among the reserves (Fig. 5*a*). Ninety-four per cent of the reserved productive forest land contained forests > 100 years old, 85% was classified as having a value for conservation (Table 3).

With a protected proportion of 5% (*ca.* 430 ha), the reserves encompassing four of the six most highly valued areas were enlarged, and four of them could be connected in pairs (Fig. 5*b*). In addition to the 19 ha of dry sediment with pine, it was also possible to establish a 24-ha reserve in a relatively rare and sensitive, but species-rich forest type, *i.e.* a spruce-dominated stand on wet ground, with many natural structures unaffected by cutting.

Protection of 15% (*ca.* 1300 ha) of the productive forest land made it possible to establish a 900-ha reserve in the central part of the studied landscape (Fig. 5*c*). Because of the distribution of stands with conservation value, the reserve had a relatively complex shape. It contained two of the areas with conservation value class 1 and a set of biotopes characteristic of the boreal Swedish forest landscape of today, *i.e.* managed young, medium-aged and old stands, large mires, lakes, and a fairly pristine stream. A new, relatively large reserve (170 ha), mainly made up of stands with conservation value class 3, and including several patches with conservation value class 2, was established in the eastern part of the studied landscape.

With the protection of 25% (*ca.* 2180 ha) of the productive forest land, the 900-ha reserve in the 15% case was increased to about 1750 ha (Fig. 5*d*). This resulted in a higher area : perimeter ratio of that reserve, at the expense of the inclusion of large areas with stands ≤ 50 years. A further result was the protection of a large



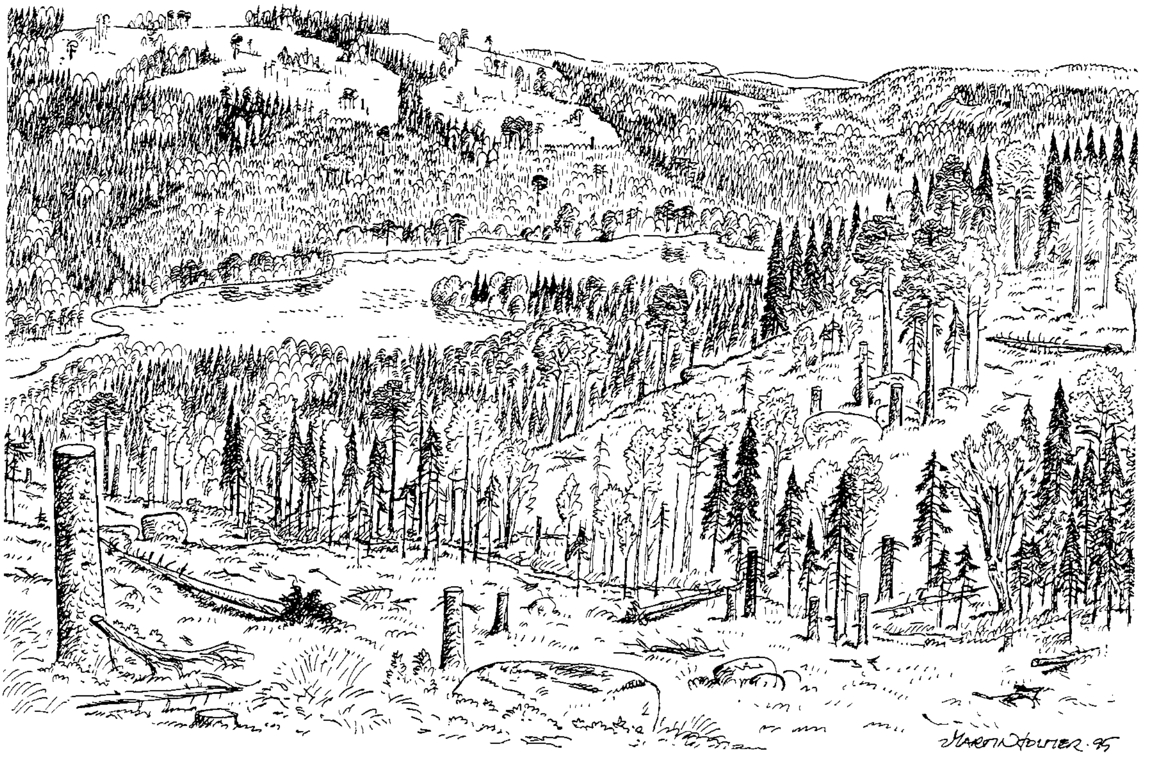


Fig. 4. In the HTP option (top), landscape patches will in the long term be more homogeneous and have more distinct boundaries than in the MTP option (bottom).

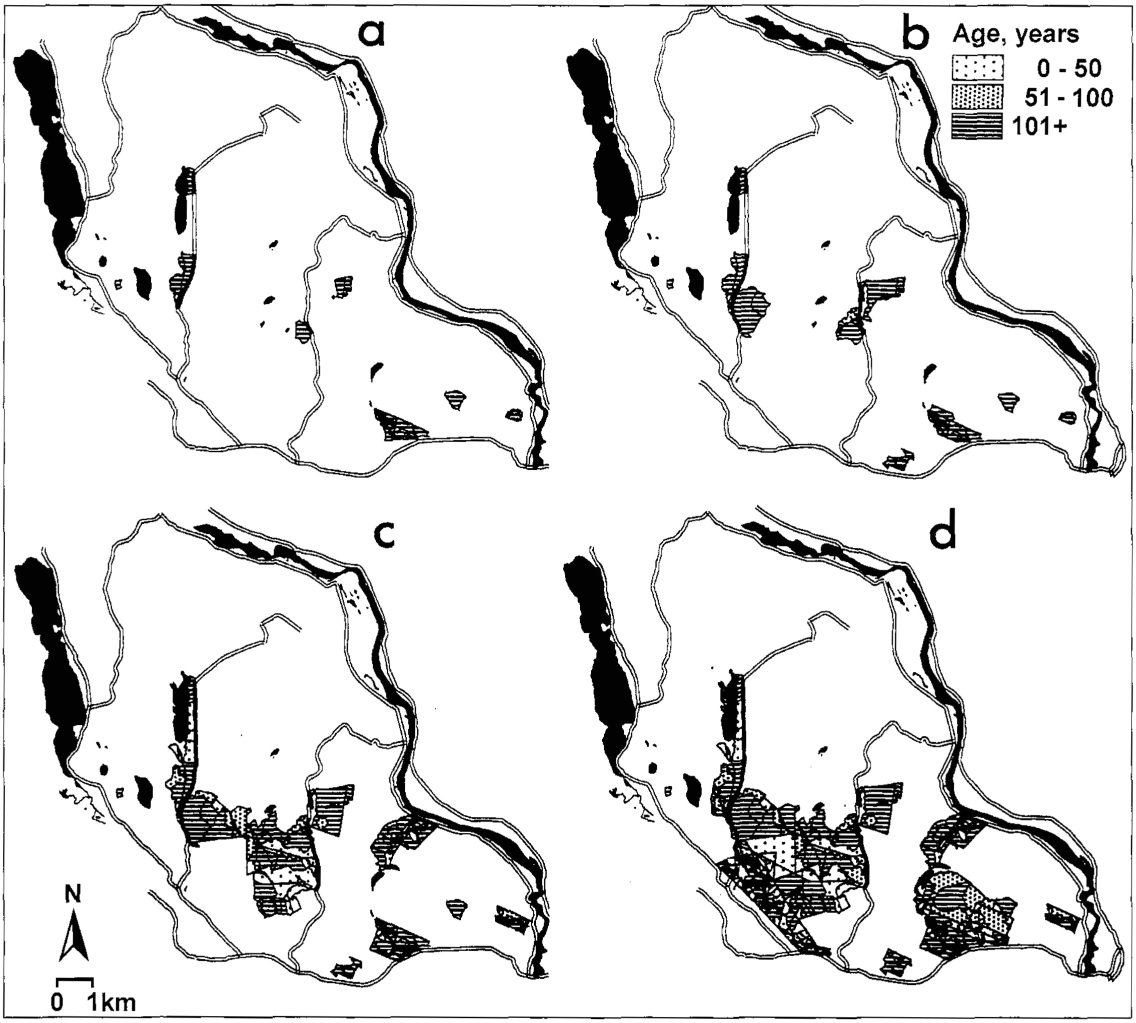


Fig. 5a–d. Protected areas in the PA approach, when 2.5 (a), 5 (b), 15 (c), and 25 (d) per cent of the productive forest land was reserved. ■ Lakes and rivers, main roads.

Table 3. *Percentage of reserved area by land class (productive forest land (PFL), mires or lakes), ageclass (on PFL), and conservation value class (CVC) in per cent, when 2.5%, 5%, 15% and 25%, respectively, of the landscape's PFL was reserved in the PA options*

Proportion protected PFL	Land class			Age class			Conservation value class			
	PFL	Mire	Lake	–50	51–100	101–	CVC1	CVC2	CVC3	No CVC
2.5	99	1	0	3	3	94	49	23	13	15
5	95	5	0	1	6	93	24	16	44	16
15	85	11	4	24	13	63	9	9	41	41
25	89	9	2	27	20	53	5	6	31	58

proportion of the stream system, the habitat of the vulnerable mussel *Margaritifera margaritifera* L. In the 15% case, three reserves in the eastern part of the studied landscape were connected to form a 650-ha reserve.

Landscape Planning (LP)

The LP approach used is a development of the 'key habitat–corridor model' which is based on principles of island biogeography and landscape ecology (Fries *et al.*, 1998). It is a spatially explicit model, based on existing areas with conservation values or other areas of conservation interest. In essence, these patches constitute sources for the dispersal of rare and threatened species and, whenever this is justified, can be linked together by corridors. A conservationally valuable area can be supported by zones, functioning as buffers or restoration zones.

In the LP approach, areas were protected as a static element (*i.e.* reserves) to provide, among other things, habitats for species dependent on the stable conditions present in undisturbed spruce forests. Furthermore, to secure the continuity of successional biotopes, a dynamic element (in the sense that forest types move through time within the landscape) was formed by means of prescribed burning and management of areas rich in deciduous trees.

As a component in the static element, a 357-ha reserve was formed, which included upland sites, mires, a lake, and parts of the stream which drains it (Fig. 6*a*). The reserve also included two of the six areas in the landscape with the highest conservation values, and the only mire in the landscape with documented high floristic values. On the third of the reserve's productive forest land that is moist or wet, spruce forests regenerated by gap dynamics are already present or assumed to be developing.

Another static part is based on five streams which are either relatively pristine, have suitable edaphic conditions or are situated so they can play a key part in a landscape plan aimed at nature conservation (Fig. 6*a*). Buffer zones were established, averaging 25 m on both sides of the streams. This resulted in the preservation of 64 ha of productive forest land and 24 ha of mire, and therefore added 88 ha to the permanently reserved area. Together with protected forest land, mires, lakes and relatively narrow restoration or buffer zones within the MTP approach, these streams will contribute to a stable network of undisturbed forest in the landscape. On 28% of the productive forest land in the stream buffer zones, stand age was ≤ 50 years, on 38% it was 51–100 years, and on 34%, >100 years. Consequently, it will take a long time before these buffer zones will contain forests with relatively high frequencies of natural features.

The last static part of the LP approach was the preservation of the four areas with conservation value class 1, which were not included in the 357-ha reserve and the 5.2 ha *Cladonia parasitica* habitat (Fig. 6*a*). These five areas include both fire-influenced sites and 'fire refugia' (Segerström, Bradshaw, Hörnberg & Bohlin, 1994). They were somewhat enlarged to reduce their perimeter : area ratio. The five areas added 140 ha of productive forest land to the permanently reserved area, which in the LP regime therefore encompasses 569 ha, of which 352 ha is productive forest land.

The dynamic part of the LP regime regulates the flow of successional biotopes dominated by deciduous trees or spruce. This was done by prescribed burning and by extending rotation length in some stands rich in deciduous trees.

During the first 50-year period, 20 selected stands, with a mean size of 12 ha, were burned (*i.e. ca.* 5% of the final harvested area; Fig. 6*b*). On the sites included in this fire plan, 25% of the standing volume was retained. To achieve variation in the results after burning, fire was used on sites with varied distribution of tree species (range 0–20% of deciduous trees), site index (range 17–23 m in dominant height at a total age of 100 years), soil moisture (32% dry, 55% mesic and 13% moist or wet productive forest land) and topography (nine stands on flat ground, nine in slopes, and two on ridges). An important consideration, which restricts the choice of sites to burn, is the desire to keep edges with a high fire hazard as short as possible. Roads, mires, lakes and stands ≤ 25 years old were considered safe (Schimmel & Granström, 1996), while stands >25 years old, bordering prescribed burning areas, were assumed to need protection. For all planned fires, a total of *ca.* 22% of the edge length (range 0–63%) will need extra measures, such as watering or removal of fuel, to prevent the spread of fire. This is the main reason why regeneration costs for prescribed burning were increased, compared with the cost of mechanical scarification and planting.

To bridge the age gap between existing late fire successions and those which will be initiated by prescribed burning, the development of deciduous trees and other natural structures typical of fire successions was enhanced in 20 stands with a relatively large proportion of deciduous trees (Fig. 6*b*). The older (total age range *ca.* 70–160 years) of the 20 stands have conservation

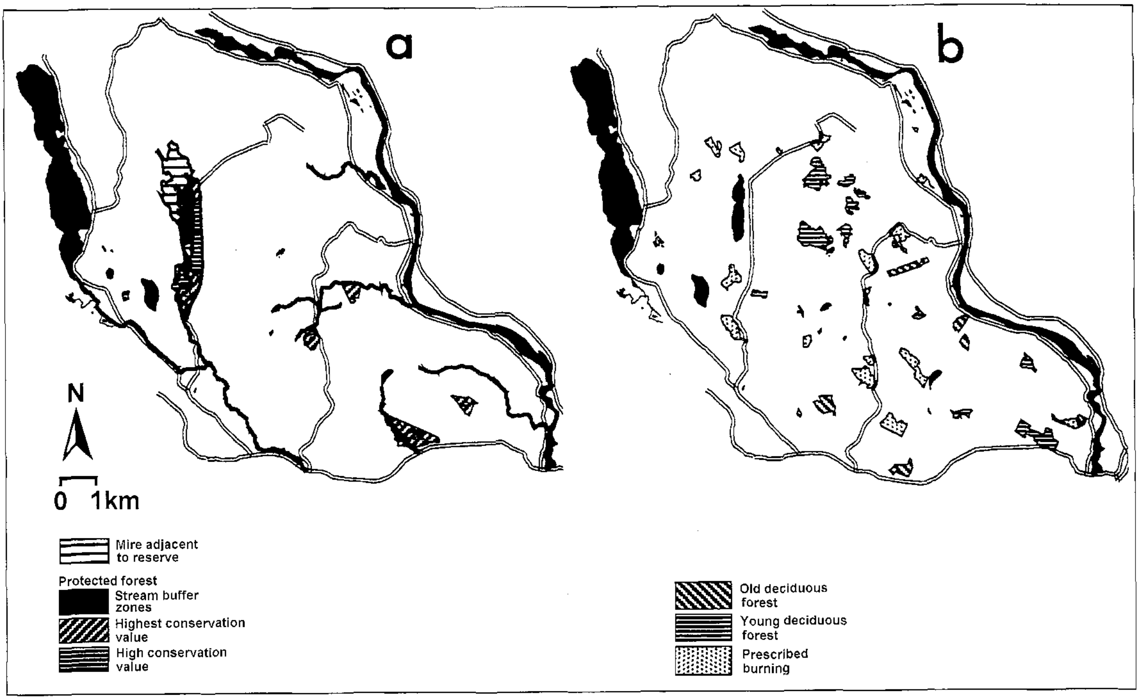


Fig. 6a–b. The static (a) and the dynamic (b) parts of the LP option. The static part includes protection of the six areas in conservation value class 1, a 357-ha large reserve (with a relatively large proportion of moist or wet productive forest land and mires), and buffer zones (mean width 50 m) around five of the landscape's streams. The dynamic part (in the sense that forest types move over time within the landscape) includes prescribed burning of finally harvested areas to stimulate natural regeneration of deciduous trees, and a management which encourages the development of old deciduous trees in 'younger' and 'older' stands that are rich in deciduous trees. ■ Lakes and rivers, ⌋main roads.

values related to old aspen (*Populus tremula* L.) and goat willow (*Salix caprea* L.). These stands make up 92 ha (1.1%) of the productive forest land. All but two of them have far exceeded the optimum age for final harvest, which, in combination with the fact that the deciduous trees have not been removed by thinning, is the reason for their having a value for conservation. The younger (total age range *ca.* 25–75 years) of the 20 stands are dominated by conifers, but contain on the average 32% deciduous trees, of which >90% is birch (*Betula pendula* Roth and *B. pubescens* Ehrh.). These stands make up 205 ha, *i.e.* 2.4% of the productive forest land. Future thinnings in these stands should aim at keeping deciduous trees and thinning out conifers. They are assumed to play a key part in retaining species which depend on deciduous trees, including old or dead ones. The rotation length for these 20 stands was extended by about 50% compared to the economically optimal rotation age, which typically is 110 years in the region.

Evaluation of effects on biodiversity

The effect of each management regime on biodiversity was assessed in two steps. The first step was to assess the future occurrence of natural stand or landscape features of significance to animal and plant diversity in three main natural forest types in boreal Sweden: (1) Scots pine forest on dry or mesic sites, (2) forests on mesic sites dominated by deciduous trees or Norway spruce, and (3) Norway spruce forests on moist and other sites, regenerated by gap dynamics (see Fries *et al.*, 1997; Table 1). The result of each management regime was deduced from the way in which they were specified (see Table 2). The assessments were expressed as 'large' or 'small' decreases or increases in the occurrence of the feature, *e.g.* continuity of old spruces in the spruce forest type.

In the second step, which we consider to be the actual analysis of the impact of forestry on biodiversity in the landscape, the results of the first step were referred to the Red-listed species found when the landscape was inventoried. Ecological groups of species were formed, based on the forest type in which the species occur naturally, and on significant features on which they mainly depend (see Table 1). For each group, the long-term (*ca.* 100 years) changes were assessed for population sizes within species or number of species. Four classes of change were used. These included: extinction or large decrease, no change, relatively small increase, and relatively large increase.

Because habitat functions (McComb, 1992) were not available for those Red-listed species which were found when the landscape was inventoried, these assessments can only be referred to species on the basis of general knowledge about the ecology of each group of species. This knowledge varies between species, and well-defined critical limits concerning, *e.g.* the availability of habitats or substratum or dispersal ability, are unknown. Nevertheless, stand and landscape feature formed by each management regime were compared with the habitat requirements described in the literature (Ehnström & Waldén, 1986; Ahlén & Tjernberg, 1996; Larsson, 1997; Hallingbäck, 1998; Aronsson, 1999; Thor & Arvidsson, 1999). There are, however, additional problems associated with assessing the effects of the management regimes on species occurring in the studied landscape. One problem arises when assessing whether or not species present in today's semi-natural stands will persist under protection from cutting. Such a population may already be so small that it is doomed to extinction (Soulé, 1987). Another problem is to assess the effects of different proportions of protected areas on Red-listed species. The quality of the forest in the matrix probably influences all of the abovementioned aspects of the effects on the species considered. A general opinion is that an increase in the amount of natural forest features in the managed matrix, as in the MTP approaches, improves the chances of preserving the natural flora and fauna of an area (*e.g.* Liljelund *et al.*, 1992; Haila, 1994).

Evaluation of effects on timber production

The Forest Management Planning Package (FMPP; Jonsson, Jacobsson & Kallur, 1993) was used for evaluating effects on timber production. This system was originally developed for strategic planning of timber production at a company level. It is made up of interconnected modules for forest inventory, forecasts, and optimisation. The goal function maximises net present value (NPV). Economic output (*e.g.* NPV and net incomes), annual harvest, and forest state (*e.g.* growing stock and tree-species distribution) are outcomes of the FMPP calculations. In principle, the planning horizon is infinite.

Depending on the initial forest state, NPV maximisation can generate an uneven net-revenue profile and, consequently, an uneven flow of timber. When mathematical programming, such as linear programming, is used, constraints on the variation of the net income over time are typically entered. In the FMPP, the 'Jacobsson algorithm' was the original optimisation routine (Jacobsson, 1986). Linear programming is now also available in the system. In the present study, however, the Jacobsson algorithm was used. When this algorithm is used, the net income profile over time is controlled by a 'smoothness parameter' b, $(0 < b \leq 1)$ where $b = 1$ implies maximum NPV without any restriction on the net-revenue profile, *i.e.* a plain NPV maximisation. The b parameter was set at 0.8 and the real interest rate to 2.5%. Economic data used (wood price lists for delivery in 1993–1994, regeneration costs, and harvesting cost functions) were considered representative for the region.

Normally, the FMPP uses a stratified sample of stands. For each sample stand, a large number of forecasts with varying numbers, timing, intensity (proportion of basal area removed) and method (selection of tree species and tree size) of thinnings and timing of final harvest, is generated. Since an individual tree-growth model is used (Söderberg, 1986), it is possible, by applying different thinning regimes, to generate a broad range of forecasts of stand development. The next forest generation can either be regenerated by planting, by natural regeneration under coniferous seed trees or by natural regeneration of mainly deciduous trees. In the optimisation, the set of forecasts thus generated makes up the set of feasible management options. The management regimes designed in the present study to enhance conditions for conserving biodiversity, were applied in the FMPP as: (1) the design of the set of feasible management options and

(2) the design of strata (after the field survey) and the areas in the various strata. The latter is described below.

Strategic planning using the FMPP is normally performed without any spatial considerations, *i.e.* consideration of the geographical location of stands. In the present study, various areas were affected by different silvicultural treatments, depending on the management regime applied. For flexibility in planning, although one based on a single sample of stands, the FMPP was modified. For the study area, a complete digital forest map and stand register were created from map and stand data from the forest companies and, in the case of non-industrial private land, from the 'General Forest Inventory' (Lämås & Fries, 1995*a*). A stratified sample of stands was inventoried by an objective method (probability sampling). The inventory was carried out as follows: First, all stands were classified according to conservation criteria, the amount of deciduous trees, soil moisture and ownership. The first three features were mapped by interpretation of colour infrared aerial photographs. Secondly, within each class, the stands were divided into strata on the basis of age and volume in the stand register. Thirdly, within each stratum a number of sample stands was allocated, then selected by PPS-sampling (Probability Proportional to Size; stand area was the size variable; Table 4), *cf.* Lämås & Fries (1995*a*). In all, 63 of 844 stands were inventoried. On average, eight circular plots with a 10-m radius (5 m in sapling stands) were measured per stand.

The flexible planning process was arrived at by creating new strata and artificial sample stands according to the following procedure:

(1) Areas designated for specific management regimes, such as (unmanaged) reserves, prescribed burning, and thinning regimes to encourage deciduous trees, were marked as different layers in a geographic information system (GIS; see example in Fig. 5 and 6).

(2) By means of the GIS, new strata were created at the intersection of areas designated for specific regimes and the original strata (the latter related to the stands; Fig. 7). The area of the

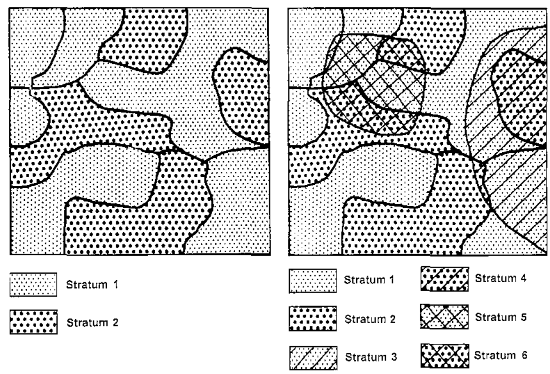


Fig. 7. A schematic forest map, with stands divided into original strata (left), used for the field survey. In each stratum, a number of sample stands was inventoried. In the planning process, areas designated for specific management (reserves, prescribed burning, *etc.*) were marked out independently of stand boundaries on the forest map (hatched areas; right). At the intersection of the original strata and areas designated for special management, new strata and related artificial sample stands, were created.

Table 4. *As a base for calculations of potential cut, a sample of stands was inventoried. All stands were classified according to a number of criteria; a stratified sample of stands was then chosen in each class. (PFL denotes productive forest land.)*

Stand class	Condition for selection	Total area ha	Proportion of PFL %	No. of strata	Total No. of sample stands
1	Stands considered most valuable for nature conservation[a]	612	1	3	3
2	Remaining stands of value for nature conservation[a]	1155	13	5	12
3	Remaining stands rich in deciduous trees[b]	865	10	4	10
4	Remaining stands with wet or moist ground[a]	686	8	5	10
5	Remaining stands owned by non-industrial private owners[c]	1683	19	7	14
6	Remaining stands (company-owned)	4216	49	6	14
Total		8666	100	30	63

[a] Colour infrared aerial photo-interpretation was used for the classification.
[b] Colour infrared aerial photo-interpretation and the stand register were used for classification.
[c] Stand register was used for classification.

original stratum was reduced by the area of the new stratum or strata. Consequently, a stratum could be entirely replaced by a new stratum or new strata. After this step, the entire forest area was divided into original or new strata.

(3) Sample-plot data from the original stratum were allotted to each new stratum. First, artificial sample stands were created in the new strata. The number of artificial sample stands in each new stratum was equal to the number of sample stands in the corresponding original stratum. Secondly, sample-plot data were randomly chosen from a true sample stand in the original stratum, and allotted to the artificial sample stand in the new stratum. For example, plots 1, 3, 7 and 8 from sample stand k in original stratum i, made up plots 1, 2, 3 and 4 in the artificial sample stand k in the new stratum j. Within a new stratum, plot data were allotted until the criteron: $n \geq N\ a \cdot A^{-1}$ was fulfilled. Here, n and N denote the total number of plots in the new and the original stratum, respectively; a and A denote the area in the new and the original stratum, respectively. By this procedure, artificial stands in a stratum could receive different proportions of plot data from their corresponding true sample stand. However, a minimum of two plots was allotted to each artificial stand.

After this procedure, strata with related original or artificial sample stands were available for the entire studied landscape. The largest number of strata (original or new), sample stands (true or artificial), and sample plots used was 101, 225, and 850, respectively. These numbers were used in the LP regime. In the NPA + HTP regime, where the planning process was based on original strata and true sample stands only, the corresponding numbers were 30, 63, and 503, respectively (*cf.* Table 4).

Results

Effects on biodiversity

The clearfelling system used in the NPA + HTP regime (Table 2) leads to the destruction of all natural spruce forest features considered important for animal and plant diversity in this type of ecosystem (Table 5). The assessed consequence is extinction of the 18 Red-listed species confined to this forest type (Table 6). This assessment assumes that in stands of forest types dominated by deciduous species or spruce, logs which today act as a substratum for wood-inhabiting fungi, will be lost as a result of clearfelling. Prospects for the persistence of features and associated species are little increased by the introduction of modified silvicultural methods. The probability for persistence increases substantially, however, if spruce sites are protected from cutting, as in the PA options. An increase in the protected proportion of productive forest land in the landscape, from 2.5% to 25% in the PA options, and to 4.1% in the LP option (excluding minor patches withdrawn from logging in the MTP options), increases the conservation possibilities for Red-listed species associated with the spruce forest type. The Red-listed species linked to the landscape's riparian zones will probably respond in the same way as the Red-listed spruce forest species.

Forest features dominated by deciduous trees or spruce, which are important to Red-listed species in the studied landscape, can also be assumed to be lost in NPA + HTP (Tables 5 and 6). The reason for this is that stands which at present contain old, dying or dead deciduous trees will soon be clear-felled in that management regime; such structures are not permitted to develop in a forestry system orientated towards timber production. However, the MTP options include green-tree retention, with priority given to large, deciduous trees. This will lead to a slow, but continuous, increase in deciduous tree structures which characterise late-successional stages in this forest type, which, in turn, probably leads to an increase in associated Red-listed species. These structures probably can not be preserved in the long term by the establishment of reserves alone, as in PA + HTP. In a 100-year perspective, conservation by means of reserves alone will probably lead to the extinction of most of the landscape's Red-listed species which depend on old, dying, or dead deciduous trees. Deciduous trees will normally be out-competed by the shade-tolerant Norway spruce before they become old. When spruce has occupied a site, only large-scale disturbances, such as fire or clearfelling, can re-create a stand dominated by pioneer species such as deciduous trees or Scots pine.

Table 5. *Asessed impact in the studied landscape of management regimes on features of significance to animal and plant diversity in Swedish boreal forests. Symbols indicate assessed large (–) and small (-) decreases in occurrence, and large (+ +) and small (+) increases in occurrence. Assessed 'no change' is indicated by* ±

Preferred biotope, significant feature, etc.	Management regime				
	NPA + HTP	NPA + MTP	PA + HTP	PA + MTP	LP + MTP
Spruce forest					
Old spruces[a)]	–	-[(b)]	+/+ + [c)]	+/+ + [c)]	+ [c)]
Spruce logs (or stumps)[a)]	-	± [d)]	+/+ + [c)]	+/+ + [c)]	+
Stable hydrological conditions	-[e)]	±	+/+ + [c)]	+/+ + [c]	+ [c)]
Deciduous or spruce-dominated forest					
Old (or dying) deciduous trees	–	+	-[f)]	+	+ +
Snags or logs of deciduous trees (also conifers)	–	+	-[f)]	+	+ +
Fire	–	+	–	+	+ +
Pine forest					
Pines more than *ca.* 200 years olds[g)]	–	+	+ [f)]	+	+
Snags and logs of large pines[g)]	–	+	+ [f)]	+	+
Fire	–	+	–	+	+ +
Riparian zones	-	+	+/+ + [c)]	+/+ + [c)]	+ [c)]

[a)] Often in combination with stable microclimatic conditions (Esseen *et al.*, 1997)
[b)] Shelterwood systems and the relatively narrow buffer zones used in the MTP options will not lead to stable microclimatic conditions in the stands, which is presumed to be the case for selective felling systems.
[c)] Described changes will largely be related to size of protected areas.
[d)] Spruce logs generated in NPA + MTP will occur scattered and to a small extent in mature and well-stocked stands with relatively stable microclimatic conditions.
[e)] This site type is often moist or wet and is therefore normally drained by ditching after clearfelling in the HTP options.
[f)] The feature can be preserved in the landscape if large-scale disturbances such as fire or clearfelling are introduced into the reserves. Compared with deciduous trees, pines normally become much older, which makes them less dependent on regular, large-scale disturbances.
[g)] These features are almost absent from the landscape today and can only be regenerated during *ca.* 100 years.

Our assessment is that the highest probability for preserving features important to species diversity in forests dominated by deciduous species or spruce is associated with the LP + MTP option (Table 5). In this option, deciduous trees are favoured in selected stands – including prolonged rotation times – and new 'semi-natural' stands, rich in deciduous trees, will regularly be generated by prescribed burning. This part of the LP option will, in consequence, most probably provide the continuous recruitment at landscape level of deciduous tree structures characteristic of late-successional stages in this forest type.

The introduction of prescribed burning in the MTP and LP options will probably add fire-dependent species (Esseen *et al.*, 1997), most of which are Red-listed, to the array of ecological groups of species in the landscape (Table 6). One difference between the pine forest type and the deciduous- or spruce-forest type, when the management regimes under consideration are applied, is that pine can probably remain longer in reserves than deciduous trees. On the other hand, it will take longer to generate pines more than 200 years old than to generate aspen, which can act as a host, *e.g.* for Red-listed lichens such as *Collema curtisporum* Degel.

Effects on economic return, harvest level and growing stock

In what follows, the term 'timberland' is used to denote areas of productive forest land which are not protected in reserves or small patches (including buffer and restoration zones) left in felling operations. Moreover, results are presented for a 100-year period. In the FMPP calculations, a discrete decision interval of five years was used; mean figures were therefore calculated for five-year periods. For simplicity (to smoothe short-term fluctuations), annual figures of net income and felling for ten-year periods are presented as the means of two successive five-year periods.

The highest NPV ($247 \cdot 10^6$ SEK) was generated in the management regime with no protected areas and without modification of timber production (NPA + HTP; Table 7). The conver-

Table 6. *Assessed impact of management regimes during ca. 100 years on biodiversity in the studied landscape, expressed as the occurrence of ecological groups of Red-listed species. A group is defined by preferred biotope in which it naturally occurs and significant feature on which it mainly depends. Symbols indicate a gradient in assessed occurrence of the ecological groups of species in the landscape: assessed extinction (-), assessed no change (±), assessed relatively small (+) and relatively large (+ +) increase of population sizes within species or number of species within an ecological group. Thirty-six of 42 Red-listed species found are included in the analysis*

Preferred biotope, significant feature, etc.	No. of Red-listed species	Management regime				
		NPA + HTP	NPA + MTP	PA + HTP	PA + MTP	LP + MTP
Spruce forest						
Old spruces[a]	2	-	-	+/+ +[b]	+/+ +[b]	+[b]
Spruce logs (or stumps)	14	-	±[c]	+/+ +[b]	+/+ +[b]	+[b]
Stable hydrologic conditions	2	-	±	+/+ +[b]	+/+ +[b]	+[b]
Deciduous or spruce-dominated forest[d]						
Old (or dying) deciduous trees	10	-	+	-[e]	+	+
Snags or logs of deciduous trees (also conifers)	4	-	+	-[e]	+ +	+ +
Fire	0	±	+	±	+	+
Pine forest[d]						
Pines more than *ca.* 200 years old[f]	0	±	+	+ +	+ +	+
Snags and logs of large pines[f]	1	-	+	+	+	+
Fire	0	±	+	±	+	+ +
Riparian zones, streams	3	-	±	+/+ +[b]	+/+ +[b]	+/+ +[b]

[a] Because of the slow growth-rate and probable low dispersal capacity of the two ephytic lichens found in the landscape (Esseen *et al.*, 1997), spruces should have continuity at the site.
[b] Described changes will largely be related to size of protected areas.
[c] Spruce logs generated in NPA + MTP will occur scattered and to a small extent in mature and well-stocked stands with relatively stable microclimatic conditions.
[d] Because most species in this forest type probably have a relatively high dispersal capacity, it should suffice with continuity in the landscape for the natural features noted.
[e] The feature can be preserved in the landscape during *ca.* 100 years only if large-scale disturbances such as fire or clearfelling are introduced into the reserves, or possibly if reserves also comprise stands with at least co-dominant deciduous trees younger than *ca.* 50 years. (The latter aspect favours large reserves which include large areas of young forest.)
[f] These features are almost lacking in the landscape today and can only be regenerated during *ca.* 100 years.

Table 7. *Outcomes of net present values (NPV, interest rate 2.5%), non-protected productive forest land (timberland), and mean annual harvest (MAH) during the first 100 years for the different management options*

Management option	NPV, 10^6 SEK	NPV reduction %	Timberland ha	Timberland reduction %	MAH $m^3 yr^{-1}$	Reduction of MAH %
NPA + HTP	247	0.0	8666	0.0	33 200	0.0
NPA + MTP	226	8.7	8232	5.0	31 100	6.3
PA2.5 + HTP	238	3.7	8446	2.5	32 400	2.3
PA5 + HTP	228	7.8	8234	5.0	31 400	5.3
PA15 + HTP	203	18.0	7361	15.1	28 200	15.0
PA25 + HTP	178	29.0	6489	25.1	24 800	25.3
PA2.5 + MTP	218	11.9	8023	7.4	30 100	9.2
PA5 + MTP	208	16.0	7823	9.7	29 300	11.9
PA15 + MTP	184	25.4	6994	19.3	26 200	21.1
PA25 + MTP	161	34.8	6164	28.9	22 400	32.4
LP + MTP	212	14.1	7903	8.6	29 500	11.0

sion of 2.5, 5, 15 and 25% of productive forest land into reserves, without modifying timber production on the remaining area (PA + HTP), reduced NPV by 3.7, 7.8, 18.0, and 29.0%, respectively, compared with NPA + HTP. NPV was further reduced by modified timber production on non-reserved forest land. In this case (PA + MTP), the conversion of 2.5, 5, 15, and 25% of productive forest land into reserves, led to a reduction in NPV of 11.9, 16.0, 25.4, and

34.8%, respectively. The combination of no reserves and modification of timber production on all productive forest land (NPA + MTP), reduced NPV by 8.7%. Consequently, PA5 + HTP and NPA + MTP resulted in an approximately equal reduction of NPV. In both options, 5% of productive forest land was protected. However, in the first option, the protected areas are aggregated into a number of reserves, whereas in the second option, they are dispersed as small patches left in felling operations. In the landscape planning regime (LP + MTP), NPV corresponded to a reduction of NPV by 14.1% in the NPA + HTP regime. In this case, 8.6% of the productive forest land was withdrawn from logging.

The annual net income in the NPA + HTP regime varied in the first eight ten-year periods, between $5 \cdot 10^6$ and $6 \cdot 10^6$ SEK yr^{-1} (Fig. 8*a*). Thereafter, income increased to $7 \cdot 10^6$ SEK yr^{-1}. All other regimes, except NPA + MTP, generated roughly the same net income profile, but with a downward shift. The NPA + MTP regime resulted in only a small reduction of the annual net income in the two first ten-year periods. In this case, the loss caused by reduction of timberland, *etc.*, was compensated for by earlier fellings (Fig. 8*a–d*).

The annual harvest volume in the NPA + HTP regime ranged between 27 000–41 000 m^3 yr^{-1} (Fig. 9*a*). In general, harvest volume is highly correlated with annual net income (Fig. 9*b–d*).

The predicted standing volume on timberland did not differ to any great extent between management regimes. At the time of inventory, the standing volume on productive forest land was 104 m^3 ha^{-1}. For all management regimes, the standing volume on timberland was predicted to decrease to between 87–96 m^3 ha^{-1} in the third ten-year period, then to increase to between 119–127 $m^3 ha^{-1}$ in the eighth ten-year period (Fig. 10). In the regimes with reserves, or when small patches of forest are left in the MTP regimes, the standing volume in the total landscape area will be higher. However, this was not estimated.

The proportion of deciduous trees in the standing volume on productive forest land was 11% when the landscape was inventoried. On timberland, this proportion decreased to 7% at the end of the second ten-year period in all HTP regimes. In subsequent periods, it increased and levelled out at *ca.* 10%. In the MTP regimes, the proportion of deciduous trees increased immediately and levelled out at *ca.* 15% at the end of the third ten-year period. From the eighth ten-year period, the proportion decreased, and was *ca.* 12% by the end of the 100-year period (Fig. 11). The reason for this decrease was that the thinning regime was modified only for existing stands and not for the next generation (because of technical difficulties in introducing such modifications into the FMPP). The proportion of deciduous trees in the total landscape was estimated only for the NPA + HTP regime. The empirical material originating from managed forests, upon which the growth and mortality functions in the FMPP are based, was judged not to permit accurate prediction for unmanaged forests for long periods of time. The proportion of deciduous trees in the reserves is, however, likely to decline, because the forest in the reserves is generally old (Table 3), and because deciduous trees are likely to be outcompeted by conifers, primarily Norway spruce.

The proportion of forest >80 years old on productive forest land was *ca.* 36% when the studied landscape was inventoried. On timberland and reserves together (small patches of forest protected in the MTP regimes being omitted), the proportion of forests in this ageclass first increased, then decreased until the sixth ten-year period (Fig. 12). The decrease was less pronounced in the PA25 option. In the NPA option, the lowest level of forests >80 years was 4%. After the sixth period, the proportion increased in all options. Inventory of the landscape showed that there were no stands older than 140 years. For all management regimes, stands older than 140 years were predicted to occur for some time. In the NPA regime, however, the highest proportion was less than 1%. In all PA options the proportion increased, reaching 19% in PA25 at the end of the 100-year period (Fig. 13).

Discussion

Of the many goods and services produced by the forest, only a few have been examined in the present study. Evidently, forest ecosystems provide a broad range of utilities. In the landscape

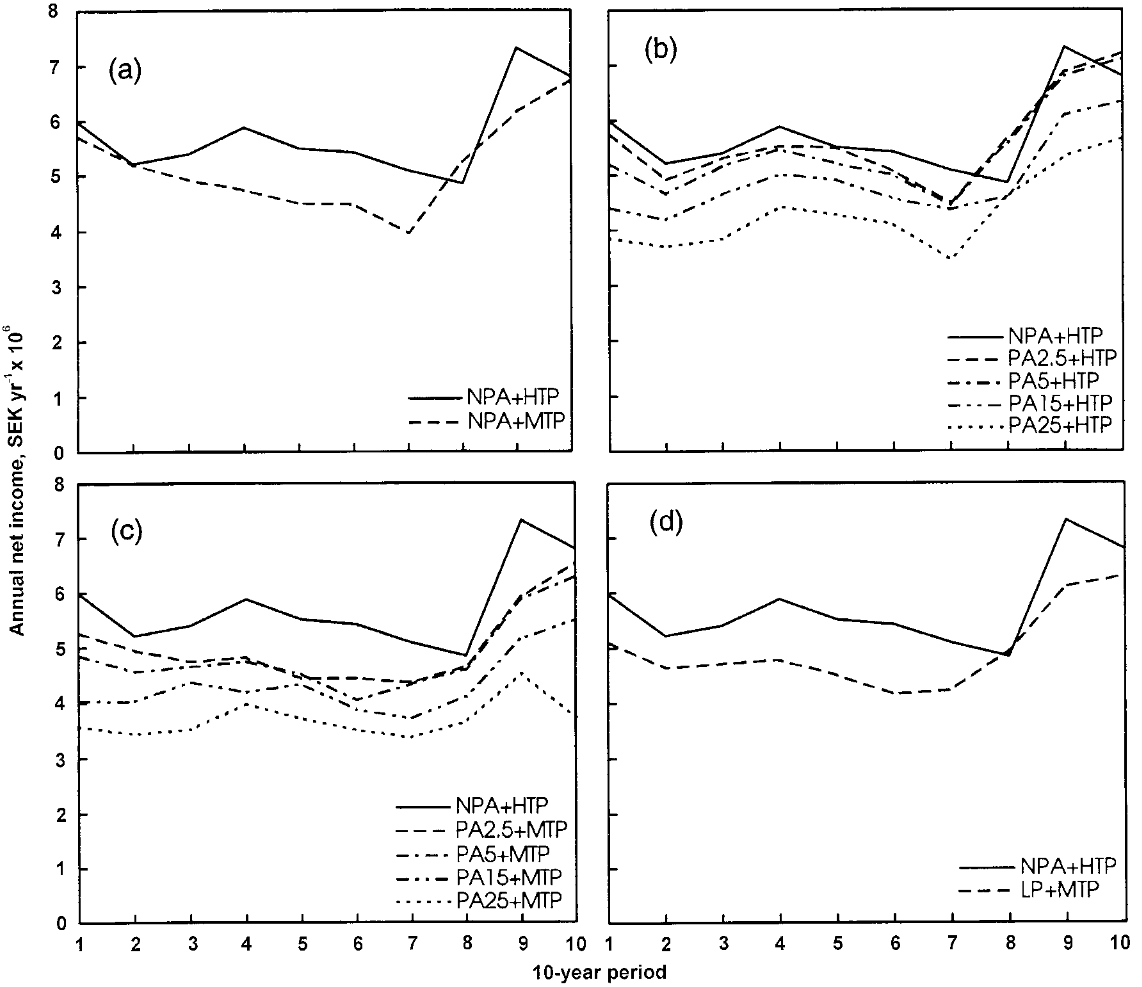


Fig. 8a–d. Annual net incomes for the different management regimes. For comparison, the NPA + HTP net revenue profile is included in all diagrams. Real interest rate 2.5%.

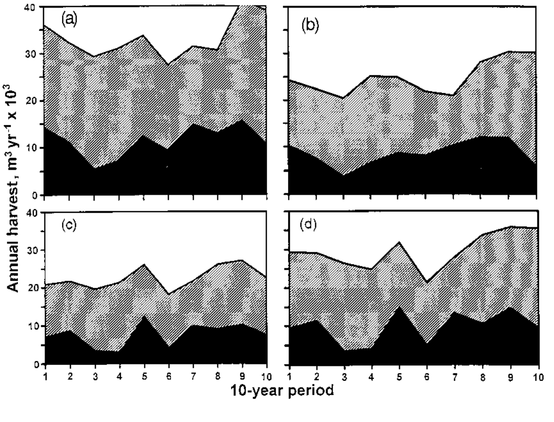


Fig. 9a–d. Annual harvest volumes in thinnings (black) and final harvesting (hatched) for the management regimes NPA + HTP (a), PA25 + HTP (b), PA25 + MTP (c), and LP + MTP (d).

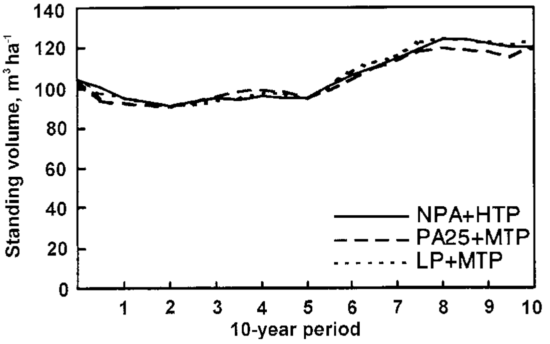


Fig. 10. Standing volume on timberland for three management regimes.

considered here, hunting is a valuable recreation for local people and visitors; there is a ski resort, and the area is used for reindeer husbandry in

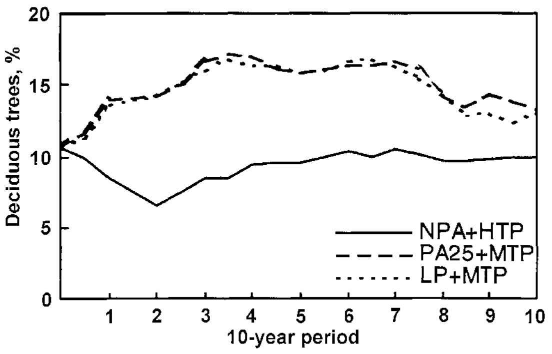


Fig. 11. Proportions of deciduous trees of the standing volume on timberland for three management regimes.

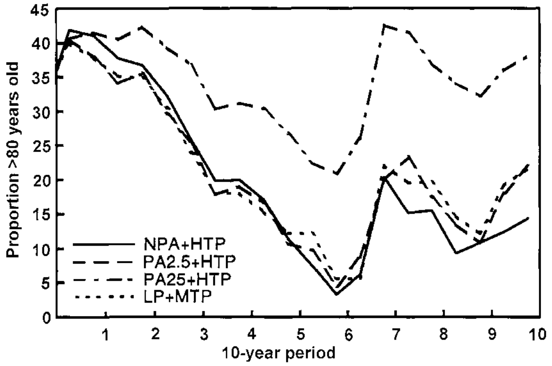


Fig. 12. Proportions of productive forest land (including reserves, if any, but excluding small patches of forest protected in the MTP regimes) >80 years old.

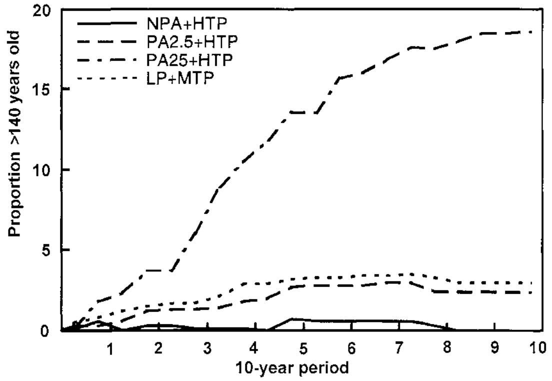


Fig. 13. Proportions of productive forest land (including reserves, if any, but excluding small patches of forest protected in the MTP regimes) >140 years old.

winter. The total number of objectives and management options is therefore vast. Maintenance of biodiversity is, however, focussed at both the local and the global level, and timber production is of great importance to both individuals and society in the region. These are the main reasons for focussing on these topics in the present study. High-yield timber production options, involving intensive timber production with the use of fertilisers, and vegetatively propagated or transgenic material or both on part of the area were, however, not considered. Such options have been proposed as a means of compensating for losses in timber production caused by nature-conservation activities (*cf.* Gladstone & Ledig, 1990).

Effects on biodiversity

The results indicate that continuation of the single objective commercial forestry, until recently characteristic of Sweden, on all productive forest land (*i.e.* NPA + HTP) for *ca.* 100 years, will eliminate most of the remaining features of significance for the Red-listed species in the landscape studied (Table 5). This will therefore most probably lead to the extinction of these species (Table 6). Modification of timber production (*i.e.* the MTP approaches; *cf.* Table 2) means that natural features are maintained or created outside reserves. It is, however, uncertain whether such actions will lead to the assumed preservation of Red-listed species which presently occur. One reason for this uncertainty is that there are scarcely any quantitative data on the effects of these modifications on Red-listed species. A further reason is that the qualities of the natural features maintained or created were not explicitly defined in the present study; this, in general, is difficult. Modified timber production (an MTP approach), however, appears to be insufficient for those Red-listed species which depend on continuity of trees on the site. In the studied landscape, the two pendent lichens *Ramalina thrausta* (Ach.) Nyl. and *Bryoria nadvornikiana* (Gyeln.) Brodo & D. Hawksw. serve to illustrate the situation. Both of them use spruce branches as a substratum and depend on relatively stable microclimatic conditions for their existence (Thor & Arvidsson, 1999); they are likely to become extinct if their habitats are not protected from felling (except for the removal of a few individual trees). To maintain these lichen populations, it may be necessary to protect their habitats from negative external effects, by establishing buffer zones of mature forest or by increasing the extent of the habitats by means of restoration zones, in which typical natural structures are enhanced. The introduction of areas protected from felling (*i.e.* the PA approach), is therefore needed to preserve species associated with old spruce in natural spruce forests regenerated by means of gap dynamics.

Species other than those associated with features typical of this type of spruce forest will also be favoured by reserves in which old forest can develop, *e.g.* the non-migratory tits *Parus montanus* Conrad, *P. cinctus* Boddaert and *P. cristatus* L. (Haila & Järvinen, 1990; Pettersson, Ball, Renhorn, Esseen & Sjöberg, 1995). The probability for many of these species to maintain viable populations is likely to increase with an increase in the proportion of reserved productive forest land. There may, however, be a threshold for species richness and population size for birds and mammals, at *ca.* 10–30% of suitable habitat remaining in a fragmented landscape (Andrén, 1995; *cf.* also Jansson, 1999). The threshold value is probably related to habitat quality and landscape geometry. Habitat quality is probably a critical factor for maintaining biodiversity in the forests of northern Sweden. If the remaining stands regenerated after natural disturbances in northern Sweden are not protected or their rotations extended, almost all of them will have been felled within the next 30 years. Although these stands have, in most cases, been thinned at least once, they contain a legacy of structures which does not occur in stands initiated by clearfelling. In the studied landscape, the proportion of forest >80 years old is at present 36% (Fig. 12). In all management regimes, this proportion will decrease to its lowest level ($<5\%$, *e.g.* in NPA + HTP and PA2.5 + HTP) in 50–60 years. This depends to a large extent on the present ageclass distribution of the forest. Forests >140 years old will exist only in protected areas and on the poorest sites (Fig. 13). Application of the threshold concept to the studied landscape leads us to predict that there will be a decline in the number of species and in population sizes of birds and mammals which depend on old forests. One example of such species is the care-demanding capercaillie (*Tetrao urogallus* L.). Although it uses different habitats during the year, the capercaillie is negatively influenced by the reduction of mature forest areas, because it decreases the number of cocks taking part in the lek at each site, and it reduces the number of potential lekking sites (Sjöberg, 1996). Furthermore, the fragmentation of old forests and the simplification of habitat structure, increase predation pressure on the capercaillie.

To preserve features necessary to all occurring Red-listed species, the landscape must be managed both to fulfil the demands of species that require continuity in habitat conditions and, from a dynamic point of view, in a way that recognises the fire-generated dynamic in the boreal forest landscape. The landscape planning (LP) approach presented here, and the PA + MTP regime, satisfy these two demands. The PA + HTP regime fulfils the static part only, and will therefore not suffice to preserve currently Red-listed species in the studied landscape. The only way of maintaining species dependent on old and dead deciduous trees in the PA + HTP regime in the long term, is to introduce large-scale disturbances, such as fire or clearfelling, into the reserves. This has many features in common with the landscape planning proposed in the LP + MTP regime. Prescribed burning in forest reserves has during recent years been practised for the first time in Sweden (Linder, Jonsson & Niklasson, 1998). Scots pine, which is a pioneer tree, also needs large-scale disturbances to survive in the landscape for a long period of time. Because Scots pines normally become much older than deciduous trees, they can survive longer in areas protected from large-scale disturbances compared, *e.g.*, with aspen or birch. The reason why so few Red-listed species associated with large, old or dead pine trees were found in the studied landscape, is that there are scarcely any such trees left. Pines, especially large pines, have been the most valuable commodity since large-scale fellings began in the region in about 1850 (Tirén, 1937).

In managing a forest ecosystem, maintenance of biodiversity can be approached in two fundamentally different ways; either by directing efforts towards single species, or by focussing on processes or structures on which the species depend. We have based our evaluation of the effects on the landscape's biodiversity (here with special reference to the Red-listed species in the landscape) on the 'process and structure approach'. This may be considered as 'a coarse filter' approach (Hunter, Jacobson & Webb, 1988) and is suggested, *e.g.* by Oliver (1992), to be the only method which works in practice. A species approach could lead to conflicts in the choice of a management strategy for a biotope, because the same management option could favour one species of interest and disfavour another. The coarse-filter approach must sometimes be complemented by a 'fine filter', *i.e.* actions directed towards a certain species or group of species. In the present study, the reserve including the lichen *Cladonia parasitica,* which is endemic to the landscape, may well be such an example. Most of the stands in conservation value class 1 constitute, in fact, examples of the species approach. The majority of the Red-listed species in the studied landscape live in these stands, and without protection they will be wiped out as a result of a future final harvest. The remnant habitats may function as sources for dispersal of such Red-listed species.

In a longer perspective (> 100 years), the location of some of the reserves or parts of reserves in the studied landscape may be reconsidered. The reason for this is that many Red-listed species associated with natural spruce forests today live on large spruce logs (*e.g.* the fungus *Fomitopsis rosea* (Fr.) Karst.) on sites which frequently burn and where this structure, if it ever developed, was destroyed by regular fires in the natural stages. One long-term strategy for preserving this type of species would be to relocate some of the reserves from fire-influenced sites to moist or wet sites, where natural spruce forest features, if not already present, can develop in the future (Segerström *et al.*, 1994). Species associated with deciduous trees may then be cared for in reserves managed by means of fire.

Effects on timber yield and economic return

The management regime with no reserves and no modification of traditional timber production (NPA + HTP) generated, as expected, the highest economic output (Table 7, Fig. 8). The decrease in NPV was approximately proportional to the reduction of the timberland area. However, because the proportion of reserved area with stands > 100 years old was much higher in PA2.5 and PA5 than in PA15 and PA25 (Table 3), the reduction of NPV was relatively higher when a smaller proportion of productive forest land was protected from felling. When the principle of forming large reserve units is applied to a landscape which comprises the full range of ageclasses, it is unavoidable that young stands are also included; these make a relatively small contribution to the economic outcome expressed in NPV.

The NPV arrived at depends heavily on assumptions of future costs and prices (here assumed to be constant), and on the interest rate used. The interest rate can be seen as a time preference of net incomes. In the absence of a specific decision-maker, the real interest rate of 2.5% was chosen, since it approximately generated a sustained economic return, annual harvest, and standing volume (Fig. 8–10). By comparison with the interest rate chosen, a higher interest rate generates increased net incomes in the near future, *i.e.* a downward-sloping net revenue profile over time. A lower interest rate, on the other hand, generates an upward-sloping net revenue profile.

The sustained economic return, annual harvest, and standing volume hold for all options, but at different levels. Although the standing volume on timberland is maintained, the amount of old forest will, in the case of no reserves, strongly decrease (Fig. 11*a*–*b*). The annual harvest levels and standing volume are maintained by higher stocking of stands and shorter rotations.

In the MTP regimes, the proportion of deciduous trees in the standing volume could be increased from the initial 11% to 15% on timberland in a rather short period of time (Fig. 10). This rapid increase was mainly the result of the shift in priority for felling deciduous trees in thinnings. The effect of regenerating deciduous trees on burnt areas appears later. Apart from considerations of biodiversity, the desirability of an increased proportion of deciduous trees can be based on timber production objectives. Uncertainty in timber prices is one incentive for any such increase (*e.g.* Lohmander, 1992).

Forest management planning can be based mainly on three types of calculation unit: (1) all stands within the considered area, (2) a sample of stands, and (3) a sample of plots. When samples of stands or plots are used, the accuracy of the data acquired is (or should be) known, and information, *e.g.* about single trees, is available. The main drawback to the use of samples in planning is the lack of complete spatial coverage. On a forest holding, a stand register (comprising information on stand age, volume, site productivity, *etc.*) and a corresponding forest map typically exist. Stand data are normally acquired by subjective inventory methods and, consequently, their accuracy is unknown. In strategic planning, when the potential of a resource in the long term is of interest, systematic errors in data can lead to erroneous decisions. Furthermore, data in stand registers consist in mean values for the entire stand, *i.e.* no data for single trees. Consequently, cruder models, compared to single-tree models, must be used, *e.g.* for growth prediction and calculation of economic output. Although the strength of stand-register data lies in their complete spatial coverage, problems will arise if it becomes necessary to mark out areas designated for special treatment, independently of the stand boundaries on the forest map. If no further estimates (based on field or remote-sensing surveys) are made, the different parts of divided stands will be assigned the same stand mean data. As stands rarely are homogeneous, false data will in consequence be assigned to some parts. The solution of the problem of complete spatial coverage of data, without 'static' stands on forest maps, is probably collection of the data by a combination of field inventory and remote sensing, and subsequent processing by geostatistical methods (*e.g.* Holmgren & Thuresson, 1997).

In the present study, a planning system using a stratified sample of stands was employed. After the field inventory, areas designated for special treatment could be marked out independently of the stand boundaries on the forest map. The problem of the lack of complete spatial coverage of data was solved by creating new strata and artificial sample stands. The appropriateness of this method depends on several factors, *e.g.* how stratification is carried out, on the number of sample stands, and how the artificial sample stands are created. The approach was chosen since it provided data of known accuracy as well as the ability to make calculations for most of the desired management regimes. The timber yield outcome among the management regimes applied, depended to various extents on the random procedure used to create artificial sample stand data. In all of the management regimes applied, only small areas were influenced by a random procedure. Various outcomes of this procedure will, therefore, probably affect the timber yield outcome to a small extent only.

Conclusions

The present study suggests that it is inefficient to maintain biodiversity in the type of forest landscape studied, by means of reserves only, when the remaining forest land is used for intensive timber production. Reserves cannot maintain long-term continuity of successional biotopes, and therefore do not fulfil the demands of species which depend on certain successional stages typical of this naturally fire-influenced ecosystem. This leads to the general conclusion that operational management of forest ecosystems should be adjusted according to the natural disturbances. A further reason is that timber production and nature conservation need not always be mutually exclusive; which implies that, from an economic point of view, it is not optimal to separate the two types of land use.

From the study, it is evident that knowledge of the ecology and response to habitat changes due to forestry, is imperfect for most of the species considered. There is a lack of knowledge for developing habitat models for inclusion in planning systems designed to forecast the development of biodiversity under different conditions. There is also a shortage of models for forecasting timber yield under more varying conditions than those which accompany forestry regimes that are orientated exclusively towards timber production; these, for the most part, are based on uniform stands, uniform management, *etc.* In planning systems for multiple-use forestry, it must be possible to handle spatial aspects (*e.g.* size, shape, and connectedness of patches) more efficiently than in the present study. However, the simultaneous optimisation of ecological aspects and timber production in time and space is complex (*e.g.* Hof *et al.*, 1994).

Finally, although more complete knowledge may in future be available for planning multiple-use forestry, it is ultimately the responsibility of the decision-maker to weigh the various forest values one against another. At the level of the forest owner (*e.g.* a forestry company), goals can be set according to the owner's preferences, within the framework established by society. At the national level, the identity of the decision-maker is more diffuse, and goals for the utilisation of the forest ecosystem should be set in a political process.

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Acknowledgements

This study was funded by the Faculty of Forestry, SLU, within the research programme 'Managing Forests for Industrial Products and Environmental Quality'. We thank Henrik Sporrong for his thorough field inventory of conservation values.