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RESEARCH ARTICLE

Maintenance of flying squirrel habitat and timber harvest: a site-specific spatial model in forest planning calculations

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Abstract Spatial and temporal continuity of resources often benefits both ecological and economic goals in landscape management. Consideration of multiple and conflicting goals is also needed to view the future production possibilities of forests in successful forest management. Our aim was to estimate the production potential of a planning area in Finland by examining different forest management strategies from ecological and economic perspectives using long-term forest planning calculations. Economic objectives referred to timber production, whereas ecological objectives were based on suitable habitats for arboreal Siberian flying squirrel (*Pteromys volans*). Suitable habitats were defined using an empirical site-specific model, which includes a spatial variable reflecting the availability of habitat within an individual's activity area. Five alternative forest plans were worked out with different objectives for flying squirrel habitat and timber production. The alternative plans were compared with respect to values of objective variables at the end of the planning period of 60 years and against a production possibility frontier among net present value and flying squirrel habitat. Varying objective values in our analyses resulted from different utilization of production possibilities, and the changes were in line with the objectives used. The formation of flying squirrel habitat clusters in the landscape was enhanced, and it did not always incur severe reductions in harvestable timber volume. Possibilities to combine ecological and economic goals, both spatial and aspatial, in the planning process seems to be an encouraging alternative for the long-term forest management in the future.

Keywords Finland · Spatial forest planning · Spatial objectives · Stand neighborhood structure · Suitable habitat

Introduction

The aim of landscape ecology is to examine patterns and processes at multiple spatial and temporal scales in dynamic heterogenic environments

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(e.g., Forman and Godron 1986). In fact, continuous availability of habitats can be seen as an ultimate goal for species persistence, whereas even flow of timber maintains forestry. Ecological goals, though, stem from the overall concern to maintain resilience of the ecosystem processes (e.g., Muradian 2001).

Consideration of composition and configuration of habitats in the landscape is important because species response to landscape changes may be non-linear: the species behaviour and population processes can change fundamentally if the landscape structure is changed beyond a certain threshold (Muradian 2001). Habitat loss and degradation have been implicated in most species extinctions (Tilman et al. 1994), and fragmentation of habitats, as decreasing size and increasing isolation of habitat patches, accompanies loss of habitat and exacerbates the effects of habitat loss (e.g., Harrison and Bruna 1999). As a general guideline, clusters of suitable habitat may improve species persistence in the area (Harrison and Fahrig 1995), since shorter distances between habitats often enable movement of individuals in the landscape. In addition, costs of harvesting operations may be decreased by clustering cutting areas (Borges and Hoganson 2000; Öhman and Lämås 2003).

The number of approaches for solving problems between ecological and economic goals in forest planning calculations has increased markedly during the past years. Economic objectives are most often measured straightforwardly as the net present value of the logging income. In contrast, formulation of ecological objectives has been more diverse. Ecological objectives in long-term forest planning have focused, for example, on continuous areas of old-growth forest (e.g., Öhman 2000), biodiversity (Kangas and Pukkala 1996; Carlsson 1999; Lichtenstein and Montgomery 2003) and the wildlife habitat characteristics (e.g., Hof et al. 1994; Arthaud and Rose 1996; Bettinger et al. 1999; Boston and Bettinger 2001; Calkin et al. 2002; Kurttila et al. 2002). Spatial ecological aspects in planning calculations may also relate landscape patterns to the processes of population dynamics (Haight 1995; Hof and Raphael 1997; Kurttila 2001; Nalle et al. 2004).

Focusing on an inappropriate scale may hide or bias the true ecological phenomena in question. Therefore, also the stand neighborhood definition and the formulation of the spatial goals in forest planning calculations should be based on the management problem at hand. Indeed, there exist several alternatives to define the spatial closeness (e.g., Bailey and Gatrell 1995; Calkin et al. 2002) for management units as well as to formulate spatial objectives in forest planning (e.g., Sessions 1992; Kurttila 2001; Kurttila et al. 2002).

The overall purpose of forest planning is to find a forest plan that combines the goals of the decision makers and the production possibilities of the planning area in an optimal way. From a manager's point of view it is useful to be able to construct and compare alternative future scenarios, which reflect the development of goals as well as strengths and weaknesses of each plan. The examination of the ecological potential of the planning area would be a useful starting point for forest planning (Mykrä and Kurki 1998). Our aim in this study is to estimate the production potential of a planning area in NE Finland by examining different forest management strategies from ecological and economic perspectives, and focus on the composition and configuration patterns of the area.

First, we define ecological objectives in terms of habitat preferences of arboreal Siberian flying squirrel (*Pteromys volans*). We apply an empirical site-specific spatial habitat model to planning calculations with real forest data. The model predicts the probability for the occurrence of the flying squirrel within a stand, and includes a spatial variable that describes the availability of suitable habitat within an activity area of an individual. The home ranges of Siberian flying squirrels are in general rather large, up to tens of hectares (Hanski et al. 2000), and the species occurrence also seems to be related to the configuration of habitats, at least in the landscapes in NE Finland (Mönkkönen et al. 1997; Reunanen et al. 2000). These patterns provide a meaningful application of spatial aspects in planning calculations. In addition, the Siberian flying squirrel may be considered a good example of species dwelling mainly in mature spruce (*Picea abies*) dominated boreal forests. It is categorized as vulnerable in Finland according to IUCN criteria (Rassi et al. 2001), but inhabits some managed forests. Therefore, it appears to be an ideal study species for an approach to simultaneously consider competitive goals for forestry and conservation.

Second, we form a production possibility frontier (e.g., Mas-Colell et al. 1995), a curve that in this study shows a trade-off between the net present value of cutting income and the flying squirrel habitat during the 60 years planning period. In addition to the theoretical frontier of two objectives, we define five alternative forest plans for future management of the planning area. Two plans have only ecological or economic goals, whereas in three plans both goals are combined.

Third, we relate the alternative forest plans against the production possibility frontier that helps evaluating the efficiency of alternative plans. We also compare the alternative plans with respect to values of objective variables at the end of the planning period. The whole planning area represents local population scale of flying squirrels, and we illustrate the population wide implications of alternative plans by the configuration of flying squirrel habitats. Finally, we discuss the usefulness of this approach in landscape ecological research and in decision-making processes.

Materials and methods

The site-specific spatial model

Our aim was to find a method to estimate the landscape structure for the flying squirrel. Therefore, we used a spatial habitat model that takes the surroundings of forest stands into account directly in planning calculations. We present the development of the spatial model for the flying squirrel habitat briefly, since the details of the model used can be found in Hurme et al. (2005). The model building was based on existing knowledge of habitat preferences for the flying squirrel in NE Finland. Flying squirrels prefer older, spruce dominated forests with a mixture of broad-leaved trees often situated within larger forest tracts or connected to other forest patches (e.g., Mönkkönen et al. 1997; Reunanen et al. 2000). We used stand-wise forest planning data as an information source for the forest structure. Hurme et al. (2005) found that the average size of a stand in state-owned forests in NE Finland corresponds with the average home range size, ca. eight hectares, of a female flying squirrel (Hanski et al. 2000). A total of 91 spruce-dominated stands were surveyed, and 35 of them were found occupied by the flying squirrel.

We selected three forest stand metrics as explanatory variables: area of a stand (ha) and growing stock volumes (m^3 ha^{-1}) of both spruce and birch (*Betula* sp.). We also calculated a spatial variable to estimate the area of good quality habitat in the stand's surroundings. First, we fitted a logistic regression model for the occurrence of the flying squirrel using only volumes of both spruce and birch (see model B, Hurme et al. 2005). If the expected probability of the occurrence was $\geqslant 50\%$ (using coefficients of b_0 (Constant) = –2.849, b_1 (Spruce) = 0.026, and b_2 (Birch) = 0.034), a stand was assigned as good quality stand for the flying squirrel. Second, we summed the area of good quality stands (probability $\geqslant 50\%$) within 500 m radius around a focal stand. This spatial variable Area500 thus describes the area of good quality habitat (ha) within the stand's surroundings. The radius of 500 m distance was selected due to the relatively good moving skills of the flying squirrel in forested landscapes and the species activity during the night (e.g., Selonen and Hanski 2003).

Furthermore, using logistic regression we built a spatial habitat model that is hereafter referred to as the flying squirrel habitat model (FSH-model). FSH-model included size of a stand (ha), volume of spruce (m^3 ha^{-1}), volume of birch (m^3 ha^{-1}), and the area of good quality habitat in the surroundings (Area500; ha) (see model AAREA from Hurme et al. 2005). The expected probability of the occurrence (P_{occ}) for each stand can be calculated (1)

$$p_{occ} = \left(\frac{1}{1 + \exp - (b_0 + b_1 \text{ Size} + b_2 \text{ Spruce} + b_3 \text{ Birch} + b_4 \text{ Area500})}\right) \tag{1}$$

The coefficients in the FSH-model for the expected probability of the occurrence were: b_0=–3.311, b_1=0.057, b_2=0.023, b_3=0.019 and b_4=0.020. With the FSH-model 72.5% of the flying squirrel occupancy in 91 stands was predicted correctly using 0.5 cut-off probability. FSH-model was used to estimate the quality of a stand from the flying squirrel perspective in planning calculations. The reason for using a more complex FSH-model instead of a simpler one with only spruce and birch is the importance of forested tracts for the flying squirrel: in the FSH-model the probability of the flying squirrel occurrence in a stand increases with the stand area and volume of spruce and birch, as well as with the area of good quality habitat (Area500) in the surroundings.

Finally, we divided forest stands in the planning area into two categories: suitable stands and all other stands, since we assumed that forests containing only small volumes of spruce are not likely to be occupied by the flying squirrel. The limit for suitable stands was set rather low: the volume of spruce had to exceed 35 m^3 ha^{-1}, which was about the minimum volume of an occupied stand in the model building data. All other stands that had a volume of spruce lower than 35 m^3 ha^{-1} were considered unsuitable for the species. For the suitable stands we calculated a probability of occurrence of flying squirrel using the spatial model. Stands that had a probability of occurrence $\geqslant$50% by the FSH-model were assumed to be of high quality for the species and assigned as FSH in planning calculations.

Planning calculations and the planning area

The aim in optimization calculations of forest planning is to find the best possible combination of stand treatments with respect to a specified planning area-level objective function. In this study, an additive utility function was used as the objective function. The absolute values of the objective variables were first transformed to sub-utilities by using sub-utility functions. After this, total utility is calculated as a weighted sum of the sub-utilities by utilizing the weights of objective variables (Table 1). As a result, the sub-utilities achieved from the values of the objective variables are aggregated to one measure, total utility (for more details, see e.g., Pukkala and Kangas 1993).

The used sub-utility functions were linear between the minimum and maximum values of objective variables. However, some objectives had target values. Their sub-utility functions were defined so that the minimum possible value of the objective variable produced a sub-utility of 0, the target value of the objective variable a sub-utility of 0.9, and the maximum value of the objective variable a sub-utility of 1.0 (Fig. 1).

The objective function (2) can be modelled as follows:

Table 1 Weights for the objective variables in alternative plans. FSH = flying squirrel habitat as a proportion of the total planning area (10215 ha); OFA = old forest area (over 140 years); NPV = net present value (discount rate 3%)

Objective variable	Forest service	Max FSH	Max NPV	FSH & timber	Less limits
FSH, after 1st period (%)		0.333		0.113	0.113
FSH, after 2nd p. (%)		0.333		0.113	0.113
FSH, after 3rd p. (%)		0.333		0.113	0.113
Cuttings, during 1st p. (m^3)	0.165			0.165	0.165
Cuttings, during 2nd p. (m^3)	0.165			0.165	0.165
Cuttings, during 3rd p. (m^3)	0.165			0.165	0.165
OFA, after 1st p. (ha)	0.057				
OFA, after 2nd p. (ha)	0.057				
OFA, after 3rd p. (ha)	0.057				
Broad-leaved trees, after 1st p. (m^3)	0.057				
Broad-leaved trees, after 2nd p. (m^3)	0.057				
Broad-leaved trees, after 3rd p. (m^3)	0.057				
Growing stock, after 3rd p. (m^3)	0.165		0.500	0.165	0.165
NPV (3%) of cutting income, for the whole planning period (€)			0.500		

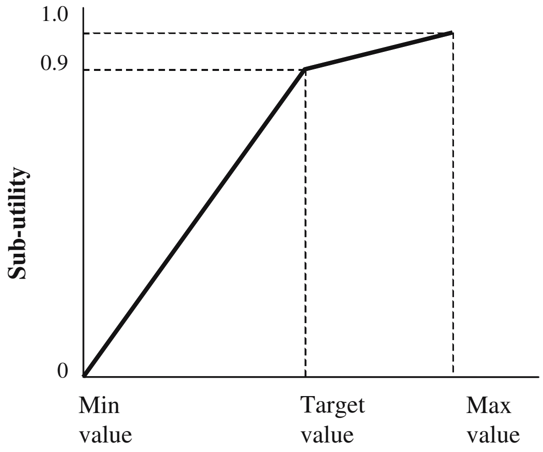

Fig. 1 Sub-utility functions were defined through the minimum value, the target level, and the maximum value of the objective variable (x-axis)

$$\text{Maximize} \qquad U = \sum_{i=1}^{I} a_i u_i(q_i) \tag{2}$$

subject to

$$q_i = Q_i(\mathbf{x}) \qquad i = 1, \ldots, I, \tag{3}$$

$$\sum_{m=1}^{M_n} x_{mn} = 1 \qquad n = 1, \ldots, N \tag{4}$$

$$x_{mn} = \{0, 1\} \tag{5}$$

where U is the total utility, I is the number of objective variables, u_i is a sub-utility function for objective variable i, q_i is the value of objective variable i (e.g., the sum of cutting volumes from the treatment schedules that are included in the current solution), and a_j is the relative importance (weight) of objective variable i. Q_i is an operator that calculates the value of objective i, $\mathbf{x}$ is a vector of binary decision variables (x_{mn} is either 0 or 1) that indicate whether stand n is treated according to schedule m, and M_n is the number of alternative treatment schedules in stand n.

The structure of the FSH-model was rather complex, since the area of good quality habitat in the stand's surroundings (variable Area500) affects the probability of the species occurrence in a stand. Therefore, we used heuristic techniques in optimization. Heuristic techniques are designed to solve complex problems and non-linear responses (e.g., Michalewicz and Fogel 2004), but they do not necessarily find the optimum. In this study, we used a combination of three heuristic techniques to find the optimal solution: the random search, simulated annealing (SA) (e.g., Dowsland 1993) and Hero (Pukkala and Kangas 1993).

SA is a variant of the descent/ascent techniques of local optimization that attempts to avoid getting trapped in local optima by allowing random deteriorations in the objective function value (e.g., Dowsland 1993). It is originally based on the cooling process of liquid material, and the terminology of the method follows the terms of the physical process (Kirkpatrick et al. 1983). Thus, the starting temperature and the speed of the cooling process (defined through the cooling multiplier) affect the stage of the material. The cooling process continues until the freezing temperature is reached and the material is solid. Similarly in SA, the search process continues until a stable solution for combinations of stand treatments is found.

The starting temperature (T_0) of SA was $T_0 = 1/(10 \times \mathrm{N})$, where N is the number of stands in the planning area. This formula is based on the assumption that the effect of a stand on the objective function value, which ranges from 0 to 1, is at most N^{-1}. The various treatment schedules of a stand often are, with several conflicting targets, nearly equally good. Therefore, N^{-1} was multiplied by 0.1, the result being a guess for the magnitude of local optima. We set the cooling multiplier to 0.90. In the starting temperature, the number of iterations equalled the number of stands and the number of iterations increased by 5% at each temperature change. The search process was stopped when a freezing temperature of $0.05 \times T_0$ was reached. The values of these parameters correspond to the parameter values that were found suitable in an earlier study (Heinonen and Pukkala 2004), where the planning problems included spatial objectives and had about the same number of stands and treatment alternatives as the planning problems of this study.

A two-compartment neighbourhood (2-opt moves) was used in SA. It means that one move of SA included a random selection of treatment schedules, which were not in a current solution, from two stands instead of only one stand. The two-compartment neighbourhood has been theorized and observed better than a one-compartment neighbourhood (Heinonen and Pukkala 2004). The effect of these two simultaneous changes were calculated and accepted or rejected according to principles of SA. Moves that improve the value of the objective function (U) are always accepted. Non-improving moves are accepted with a probability of $p = \exp((U_{\mathrm{New}} - U_{\mathrm{Old}})\ T_i^{-1})$, where T_i is the current temperature, and U is the objective function value.

The optimizations were carried out by using the Monsu forest planning software (Pukkala 2004). We searched for an optimal combination of stand treatments by sequentially applying random search, SA and Hero in the optimization process. First, we repeated the random selection of a treatment schedule (including e.g., different thinnings, final cut, or no treatments) for each stand two hundred times. Second, from the best random solution, we started the search procedure of SA. Third, when the search of SA was stopped, we performed the direct search phase of the Hero algorithm once for this solution. In Hero, all the possible treatments for neighbour stands were checked systematically, so that in the end Hero finds the nearest local optimum exactly.

The length of the planning period was 60 years, divided into three 20-year sub-periods. We used an automatic stand simulator included in the Monsu forest planning software. A final cut with the necessary post-cutting treatments (such as planting trees to confirm the growth of a new forest) was simulated when the stand age reached either the minimum age or the mean diameter required for a regenerative cut. These criteria were the same that are in use by Metsähallitus (an enterprise managing state-owned land and waters) in NE Finland. Thinning was simulated when the dominant height and basal area of a stand reached the thinning limits specified in the official silvicultural guidelines (Anonymous 1994). All cuttings were simulated in the middle of the 20-year sub-periods.

The timing of the final cuttings was varied in order to obtain more than one treatment schedule per stand and because it was possible to postpone the cuttings after a forest stand reached the regeneration age. One of the simulated treatment alternatives for mature stands was always the ‘‘no treatment’’ option. The number of schedules per stand varied from one to seven. For younger stands, the first thinning was forced to be carried out so the ‘‘no treatment’’ option was not simulated for them. As a result, some young stands had only one management option while stands approaching the mature age often had seven different management options. For the stands that were in restricted use, the ‘‘no treatment’’ option was the only simulated treatment alternative.

The area used in planning calculations is largely coincident with the data for the FSH-model (Hurme et al. 2005). The area falls in the northern boreal vegetation zone in NE Finland. It is characterized by forested hills surrounded by wetland areas, like open bogs, and the topography varies between 220 and 370 m above sea level. The planning area covers 10,215 ha of which 7,025 ha is productive forest land (annual increment >1.0 $\mathrm{m}^3\ \mathrm{ha}^{-1}$). The area is divided into 976 separate forest stands. The mean growing stock volume of the productive forest area was 64 $\mathrm{m}^3\ \mathrm{ha}^{-1}$ in the beginning of the planning period (year 2004), and the average annual increment was estimated at 2.0 $\mathrm{m}^3\ \mathrm{ha}^{-1}$. The proportions of pine (*Pinus sylvestris*), spruce and broad-leaved trees (birches, aspen *Populus tremula* and alder *Alnus incana*) were 57, 32 and 11%, respectively. The initial age distribution was as follows: younger than 20 years 16%; 20–39 years 24%; 40–59 years 25%; 60–79 years 5%; 80–99 years 2%; and older than 100 years 28%. The initial proportion of the FSH was 8.5% (870 ha). However, 3,469 ha of the planning area included some restrictions on their use, based on protection of old forests, claimed areas or other limitations. The forest area without restrictions for use (6,746 ha) had only 1.2% of FSH.

Production possibility frontier and alternative forest plans

We formed a production possibility frontier (Mas-Colell et al. 1995), which in our study demonstrates a trade-off between ecological and economic objectives. It shows the locations of efficient solutions where it is not possible to increase the value of one objective variable without decreasing the value of another objective variable. The production possibility frontier was calculated by using the area of FSH at the end of a planning period of 60 years and the net present value (NPV), from the cutting incomes of the whole planning period (3% interest rate) as objective variables. The area of FSH was maximized while different NPV values were fixed to specified levels through target values, which were defined to the sub-utility function of NPV. Thus, in the optimization, the target value of NPV acted as a constraint. The production possibility frontier was drawn for these two objective variables to illustrate the costs, which can be caused by the improvements in the proportion of FSH.

We produced five different forest plans for the planning area. Three of the plans reflect both ecological and economic goals, whereas two plans illustrate the production possibilities having only ecological or economic goals. The plans and definitions for their sub-utility functions were as follows (Table 1):

(1) ''Forest service'' reflects the present planning strategy by following some of the principles included in the landscape ecological plan prepared for the planning area's state-owned forests by Metsähallitus (Karvonen 2000). The two ecological objectives adopted from the landscape ecological plan were to maximize the area of old forest (age $\geqslant$140 years) and volume of broad-leaved trees (at the end of the three sub-periods). In the actual landscape ecological plan the corresponding objective is the area of forests dominated by broad-leaved trees but due to differences in the planning systems it was changed to a volume objective.

Economic objectives were growing stock volume (at the end of the planning period) and cutting volumes (during the three sub-periods). The large amount of younger forests (65% of the forests were $<$60 years) in the planning area decreased the cutting possibilities particularly during the first sub-period. Therefore, based on the initial age structure, forest growth and cutting possibilities of the planning area, we iteratively searched the reasonable target levels for cuttings of sub-periods. The following target levels were used: 60,997 m^3 for the first period (70% of the maximum cutting possibility during the first period); 225,780 m^3 for the second period (the initial growth of the forests in the unrestricted area times 20); and 248,358 m^3 for the third period (110% of the initial growth of the forests in the unrestricted area times 20). The minimum cutting volume produced sub-utility of 0.0, the achievement of the target levels the sub-utility of 0.9, and the maximum cutting level the sub-utility of 1.0. The other sub-utility functions (for old forest area, volume of broad-leaved trees and growing stock volume) were linear between their minimum and maximum values. All objectives were directed only to forests without restrictions for use.

(2) ''Max FSH'' examined the ecological production potential of the planning area in terms of flying squirrel habitat. Therefore, the three objective variables were the amount of FSH at the end of each three sub-periods, which were maximized in the whole planning area. Their sub-utility functions were linear between their minimum and maximum values.

(3) ''Max NPV'' shows the economic production potential of the area by maximizing the NPV of cutting income (at 3% interest rate) without any ecological goals. The growing stock volume had a target level, namely the volume reached in ''Forest service'' (Table 2), which gave a sub-utility of 0.9. These objective variables were maximized only in forests without restrictions for use.

(4) ''FSH and timber'' as a species-wise plan was similar to ''Forest service'', but the ecological objective was to maximize the area of FSH. Maximum values for the linear sub-utility functions of FSH were found from the results of ''Max FSH'' plan (see the values at the end of the three sub-periods from Table 2). The objective variable of growing stock volume had a target level, which was the same as reached in ''Forest service'' (Table 2), and it gave a sub-utility of 0.9. The ecological objective variables concerned the whole planning area and economic ones the forests without restrictions for use.

(5) ''Less limits'' estimates both, ecological and economic potential of the area. It has exactly the same objective function than ''FSH and timber'',

Table 2 Values of some objective variables in alternative plans (objectives in optimization shown in bold)

Objective variable	Forest service	Max FSH	Max NPV	FSH and timber	Less limits
FSH, 1st period (%)	14.2 (5.7)	**14.3 (5.9)**	12.8 (4.9)	**14.3 (5.9)**	**14.3 (12.9)**
FSH, 2nd p. (%)	21.0 (10.7)	**24.0 (14.8)**	20.8 (10.9)	**21.6 (11.7)**	**24.0 (22.2)**
FSH, 3rd p. (%)	25.6 (12.8)	**33.6 (24.2)**	25.0 (12.0)	**28.3 (16.8)**	**33.6 (32.1)**
Cuttings, 1st p. (1000 m^3)	**(61.6)**	(46.9)	(86.4)	**(67.9)**	**(66.6)**
Cuttings, 2nd p. (1000 m^3)	**(228.0)**	(173.1)	(204.8)	**(228.1)**	**(226.7)**
Cuttings, 3rd p. (1000 m^3)	**(251.7)**	(184.1)	(265.6)	**(251.8)**	**(249.3)**
OFA (ha)	**1930.1 (304.2)**	1931.0 (305.2)	1638.6 (12.7)	1698.3 (72.4)	1633.5 (1015.1)
Broad-leaved trees (1000 m^3)	**73.3 (40.1)**	73.3 (40.1)	64.9 (31.8)	63.8 (30.7)	66.1 (55.2)
Growing stock (1000 m^3)	**670.4 (365.0)**	864.2 (558.8)	670.5 (365.1)	**670.5 (365.1)**	**694.4 (584.5)**
NPV (1000 €)	(5379)	(3768)	**(5693)**	(5452)	(5461)

Values of OFA, broad-leaved trees and growing stock are after the third period and of NPV for the whole planning period of 60 years. FSH, OFA, broad-leaved trees and growing stock are for the whole planning area of 10,215 ha (in parenthesis for the area without restrictions, 6746 ha; 8770 ha in "Less limits"), but cuttings and NPV only for the area without restrictions. For abbreviations see Table 1. The initial proportion of flying squirrel habitat is 8.5% (1.2%)

but the treatment restrictions concerned only the forests that are protected by law, covering of 1,445 ha. In other words, the timber-production possibilities of the planning area were increased by releasing 2,024 ha of the forest area that was in restricted use in all other plans. The restrictions are usually formed to maintain ecological values by preventing timber harvest, so our aim is to examine other possibilities to reach the same values. Additional treatment schedules were simulated for these released stands similarly as for other unrestricted stands. The growing stock volume had a target level, which was the same as reached in "Forest service" (Table 2), and gave a sub-utility of 0.9.

Besides examining the outcomes of different plans and relating them against the production possibility frontier of two objective variables, we evaluated the alternative plans from an ecological perspective. We used the proportion of FSH at the end of the three sub-periods and visualized the outcome of each forest plan using theme maps. We also characterized the spatial arrangement of FSH initially and at the end of the planning period. The pattern of habitat clusters was estimated by defining a number and total size of FSH patches as separate stands or groups of stands of FSH that have a common border. We also defined an arbitrary patch size that could be of particular importance for persistence of a small population, because extinction risk of populations decreases with increasing habitat size (e.g., Lande 1993). We used a threshold of 50 ha that theoretically could foster five to six reproducing females based on average home range sizes, and calculated the percentage of the planning area covered by FSH patches at least 50 ha in size. GIS routines were used in calculating spatial arrangement of FSH at the end of the three sub-periods.

Results

The objectives applied in alternative plans were clearly reflected in the results (Table 2). For example, plans that had FSH as an objective also had the largest proportions of the habitat. In plan "Forest service" we used the area of old forest (initially 1,930 ha of which majority 1,626 ha was located within the restricted area) and the volume of broad-leaved trees as objectives, and therefore these values were at their largest in this plan. "Max FSH", however, also had high values for these objectives since flying squirrel habitats can be categorized as old forests or they have large volumes of broad-leaved trees. Furthermore, the growing stock volume was about 20% larger in "Max FSH" than in other plans: flying squirrel habitats usually have large growing stock volumes.

The proportion of FSH rose considerably during the first sub-period from the initial situation of 8.5% to about 14% within all plans (Table 2). Only in "Max NPV" was the proportion of the habitat already lower. After the second sub-period “Max FSH” and “Less limits” started to stand out by having the highest proportions of FSH, but the differences between plans were at their largest after the third sub-period. Plans “FSH and timber” and “Less limits” resulted in high amounts of FSH, while achieving timber production targets and the same levels for cutting volumes. “Less limits” achieved the highest proportion of FSH and high growing stock volume within the unrestricted area due to the larger area available.

The cutting volumes in “Forest service”, “FSH and timber” and “Less limits” closely followed the defined target levels, although slightly exceeding them (Table 2). The net present value of cutting income was clearly the largest in “Max NPV”. Although we cannot directly compare NPV values between the plans, because other plans missed this objective, we can illustrate the efficiency of alternative plans considering both NPV and FSH using the production possibility frontier (Fig. 2). Particularly “FSH and timber” is quite efficient with respect to FSH and NPV, as it is located very near to the frontier. “Max FSH” produces the maximum amount of FSH. Note that the production possibility frontier was calculated by maximizing FSH area with varying target values for NPV: target levels for growing stock volumes were not used. The location of “Less limits” above the production possibility frontier indicates the amount of production possibilities lost because of restrictions in land use. The ‘super-optimality’ of “Less limits” is an artifact because the frontier is produced including the restrictions, but however, it shows the possibilities of dynamic forest management.

Because “Max FSH” maximized only the amount of FSH, the spatial configuration is also the best that can be achieved in this landscape within 60 years using our model (Fig. 3). Compared to the initial situation where FSH is located almost completely inside restricted areas (Fig. 3A), additional habitats appeared either close to the original areas or formed larger clusters to unrestricted forest area during following sub-periods (Fig. 3B–D). The same general pattern of clustering is reflected also in other plans at the end of the planning period (Fig. 4).

The visible pattern of clustering in the end of the planning period is supported by numerical landscape measurements (Table 3). Habitat patch size was on average larger and the majority of FSH was situated within patches larger than 50 ha, especially when compared to the initial situation. The clustering was most noticeable with plans that had FSH as an objective. The largest mean patch size together with the smallest amount of suitable habitat in plan “Max NPV” can be explained by the small number of patches and their location within or close to restricted areas.

The optimizations for plans having timber production objectives were replicated five times, which facilitated examination of the consistency of the optimization process. The use of the additive objective function in optimization allows deviations in the values of objective variables so that the decrease in the value of one objective variable can be compensated by increasing the

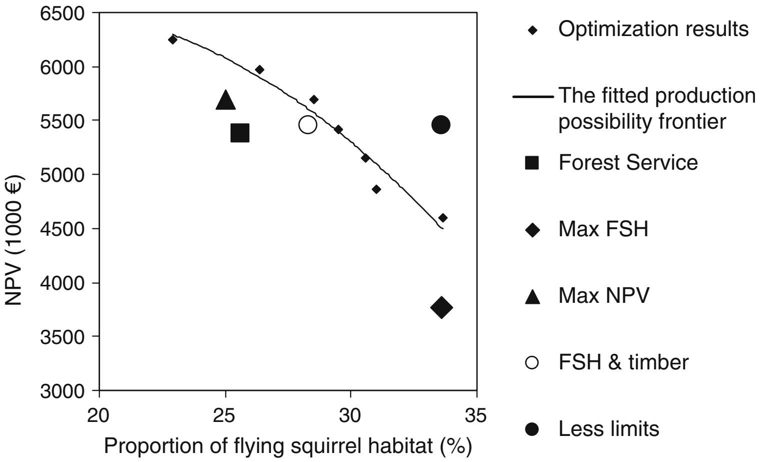

Fig. 2 The fitted production possibility frontier for NPV and flying squirrel habitat at the end of the planning period, together with the locations of alternative plans relative to the theoretical curve. The location of the “Less Limits” plan outside the production possibility frontier is a result of increasing possibilities to carry out cuttings in areas, which in other plans were in restricted use

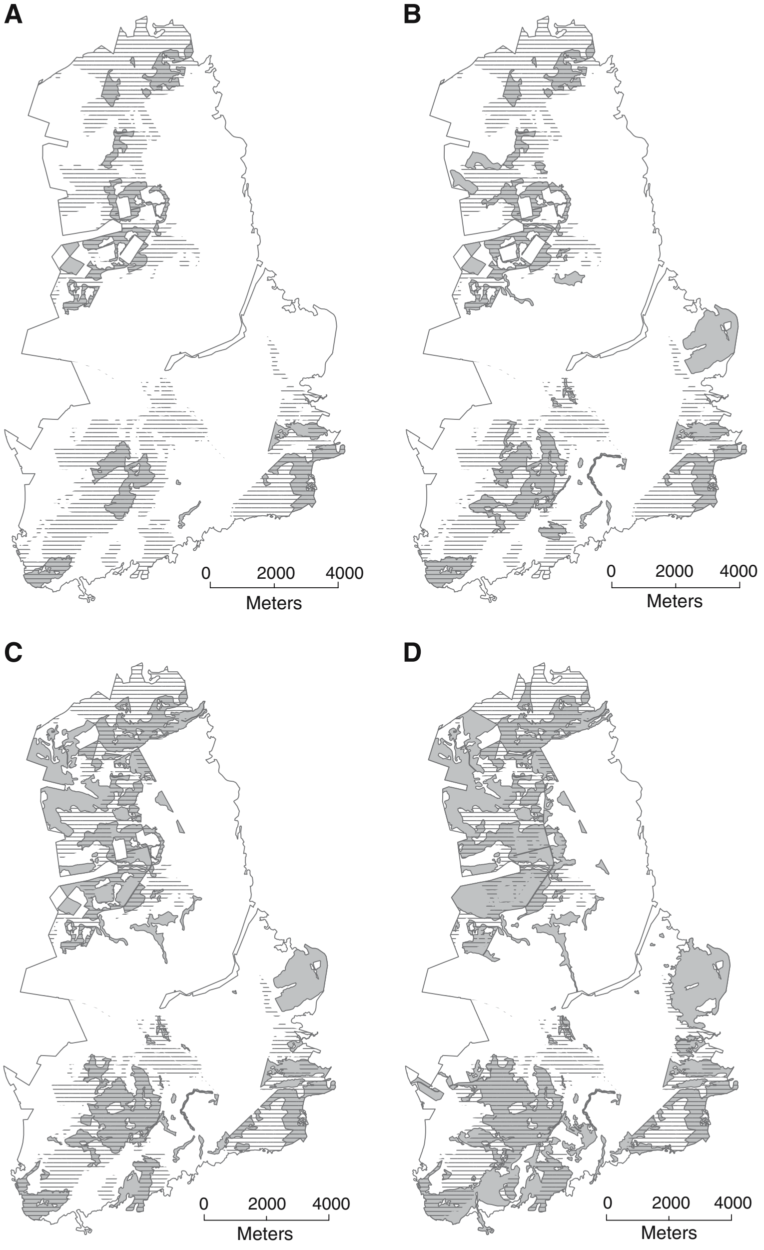

Fig. 3 The locations of flying squirrel habitats (gray) as ⩾50% probability of occurrence estimated by the site-specific spatial habitat model in plan ‘‘Max FSH’’: at the initial situation (**A**), after the 1st sub-period (**B**), after the 2nd sub-period (**C**), and at the end of the planning period (**D**). Striped areas have restrictions for use

value of another objective variable. As the alternative plans included rather different objective variables, we used a coefficient of variation as a more general way to measure the consistency of the process. The coefficient of variation in the total utility was very low in all plans: 0.6% for ‘‘Forest service’’, 0.6% for ‘‘FSH and timber’’, 0.3% for ‘‘Max NPV’’ and 0.1% for ‘‘Less limits’’. Low variation in the values of objective variables, due to e.g. defined target levels for growing stock and cutting, also probably decreased the variation of the total utility.

Discussion

Our aim was to illustrate the production possibilities of a planning area by producing a limited number of management strategies for the 60 years planning period. Varying objective

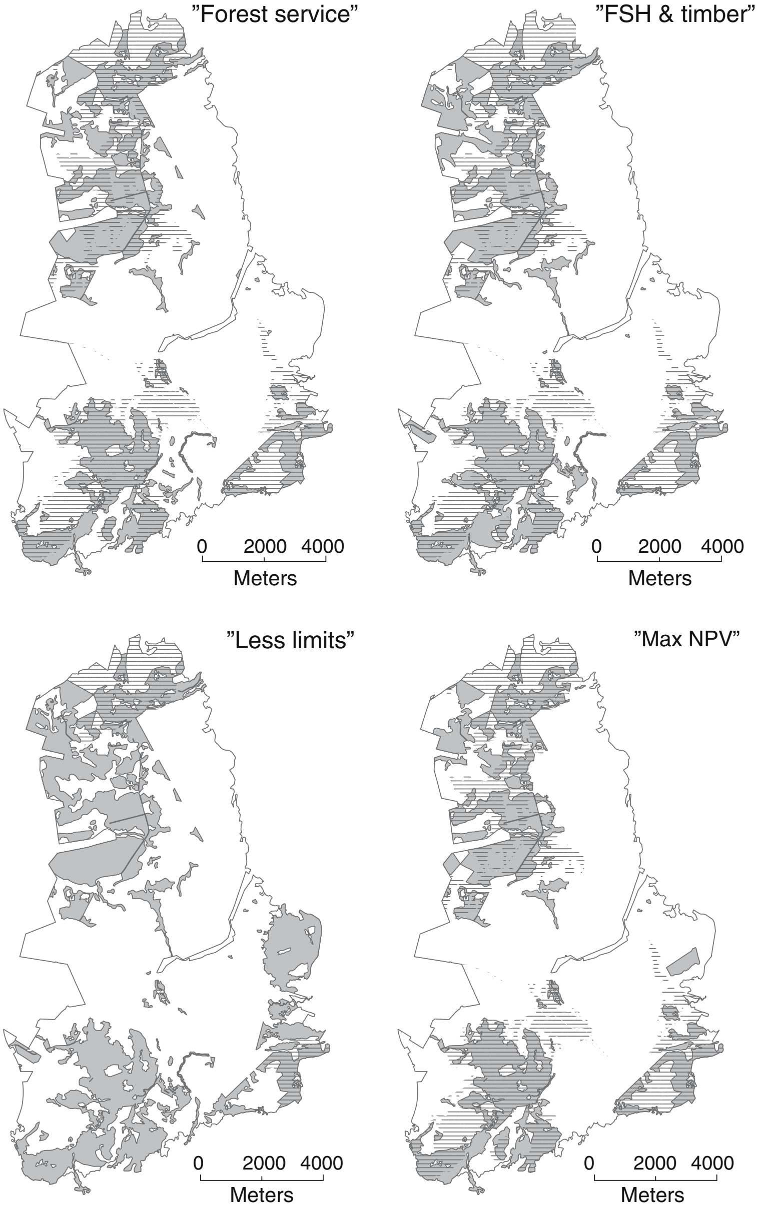

Fig. 4 The locations of flying squirrel habitats (gray) as $\geqslant$50% probability of occurrence estimated by the site-specific spatial habitat model at the end of the planning period in plans ‘‘Forest service’’, ‘‘FSH & timber’’, ‘‘Max NPV’’ and ‘‘Less limits’’. Striped areas have restrictions for use

function formulations and released restrictions for treatments in our analyses resulted changes in the utilization of production possibilities and variation in the amounts of the flying squirrel habitat. Results we observed were in agreement with the goals of the study.

From an ecological perspective, all of the plans included significantly more flying squirrel habitat that the 8.5% initially present. In fact, 25–30% habitat cover was attained under all of the plans, even in ‘‘Max NPV’’ plan where the only objective was to maximize monetary income subject to growing stock target level. Assuming flying squirrel persistence increases with habitat area, the best overall result (approximately 34% FSH) is attained under the ‘‘Max FSH’’ plan. It had FSH as the only objective and reflects the ecological capacity of the area in terms of the estimated habitat cover.

From an economic perspective, we found that monetary returns could be preserved without overly compromising FSH. However, timber

Table 3 The spatial pattern of FSH at the end of the planning period is described by habitat patch size, HPS

Spatial measure	Initial	Forest service	Max FSH	Max NPV	FSH and timber	Less limits
No. of habitat patches	27	76	82	57	72	82
HPS, mean (ha)	32.0	34.4	41.9	44.8	40.2	41.9
HPS, max (ha)	161.3	887.1	1016.9	881.5	1013.7	1016.9
HPS, std (ha)	39.8	112.4	136.2	124.3	129.9	136.2
Cover of large patches (%)	5.5	20.7	29.5	18.8	24.1	29.5

HPS indicate separate FSH stands or groups of FSH stands that have a common border. Minimum HPS is 0.03 ha, except 0.1 ha in plan ‘‘Max NPV’’. Large patches refer to patches ⩾50 ha with flying squirrel habitat, and their cover is calculated as the percentage of the whole planning area (10,215 ha)

prices may change considerably during the 60-year planning period, and the estimates of NPV losses would therefore be imprecise. Thus, we examined the location of alternative plans with respect the production possibility frontier, and found that ‘‘FSH and timber’’ was closest to the frontier. In this plan the objective was to produce both habitat and timber. This finding matches well with Juutinen et al. (2004) who showed that combining economic and ecological goals may result in cost-efficient and ecologically justified solutions in forest management decisions.

Furthermore, also the ‘‘Less limits’’ plan reached the ecological capacity (approximately 34% FSH) of the study area. Simultaneously it yielded the targeted amounts of cuttings during the sub-periods and about the same economic income (NVP) as in the ‘‘FSH and timber’’ plan. The larger area for timber production meant more flexibility to allocate harvesting to stands of minor importance for the species. This shows that other policies beyond setting treatment restrictions could be used when multiple objectives are to be optimized: if timber production potential is increased by releasing some of the reserved stands for dynamic forest management, ecological objectives may still be reached. In fact, the same forests could produce several products in space but also in time. This would probably hold true if stands could first be partly used for timber production and then for conservation, or vice versa. In addition, social considerations such as recreational or esthetic values can be included in planning calculations. However, giving up the restrictions needs careful thinking because not all ecological objectives are compatible with timber production, and it may be found socially unacceptable.

Our FSH-model used in forest planning calculations succeeded in increasing mean habitat patch size and forming habitat clusters for the flying squirrel. This suggests that suitable habitats for vulnerable flying squirrels within this landscape could exist in the future even with timber harvesting, and hence, habitat fragmentation might be avoided if spatial goals are incorporated into the planning procedure. Our results clearly illustrate the advantages to aggregate FSH in space and concentrate cuttings to other areas. The clustered pattern was partly a result of the spatial variable in the FSH-model. It made calculations more complex by increasing the amount of stands in the surroundings but on the other hand, it made evaluation of the habitat quality more realistic in biological terms. This kind of approach for spatial closeness could be used when aiming at augmenting the existing protection area network or structural connectivity of the landscape. The use of an empirical habitat model also strengthened our study: we can estimate that the FSH-model predicts 72.5% of the occurrence correctly and the uncertainty in the estimation can be assumed to be systematically distributed over the landscape. As such, the production of alternative management strategies can support planning and decision making, particularly if the uncertainty is taken into account.

However, our optimizations reflect hypothetical scenarios produced by simulations over 60 years in time. We do not know if the predicted habitats would in reality be suitable for flying squirrels, since cavity trees and aspens are essential characteristics of forests for the flying squirrels (e.g., Hanski et al. 2000). Inhabited forests often represent the late-succession stage of northern boreal forests and they contain broad-leaved trees as remains from the earlier succession stages. The youngest stand we observed occupied by the flying squirrel was 120-years-old, whereas some stands assigned as suitable in the end of the planning period hardly reached 80 years.

In addition, the management history of the forests used in model building differs from the management principles that were assumed to take place during the planning period. The original forests in our study area are naturally regenerated and have a large variation in tree species composition and spatial configuration of trees. Most of the stands reaching the status of FSH in the end of the planning period will be artificially regenerated after clear-felling, and probably will not include as much internal variation as the original forests do. The forest planning data itself seem to have a suitable scale for the flying squirrel in NE Finland, and we have some evidence that our predictive model could be applied to other regions in NE-Finland (Hurme et al. 2005). Still, we find it necessary to calibrate the predictive models with region-specific weights for model parameters or, improve the model performance with additional expert knowledge on crucial factors for the species.

Our study illustrates some of the existing possibilities to estimate production potential and to compare alternative future scenarios for the planning area. This can be offered by multi-objective forest planning techniques where both the ecological and economic objectives are simultaneously integrated into the planning calculations. The tools required to initiate these kinds of planning situations are becoming available (see also e.g., Bettinger et al. 1999; Calkin et al. 2002; Kurttila et al. 2002). Our site-specific example of a rather small landscape and one species could serve for other species preferring similar habitats. Moreover, approaches with multi-species studies and overall land use (e.g., Schumaker et al. 2004; Polasky et al. 2005) are essential when the goal is to understand some of the ecosystem patterns and dynamic processes at the landscape scale.

Through the spatial FSH-model our approach was able to cluster flying squirrel habitats and simultaneously take the other objectives set for the planning area into account. As a result, it could be used as a tool by which forest managers, decision makers and participating interest groups could learn more about the ecological and economic capacity of the planning area and interdependencies between different objectives. Possibilities to combine ecological and economic goals, both spatial and aspatial, in the planning process seems to be an encouraging alternative for the long-term forest management in the future.

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