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How reserve selection is affected by preferences in Swedish boreal forests

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ABSTRACT

It is important to consider the preferences of the various stakeholders involved when evaluating effective reserve selection, since it is largely their preferences that determine which of a given set of potential reserve networks that actually is "the best". We interviewed eight conservation planners working at the county administrative boards in each of the eight administrative counties covering boreal Sweden to establish weightings for different structural biodiversity indicators by using the Analytic Hierarchy Process (AHP). The subjective weightings were applied in a reserve selection model based on a goal programming (GP) approach. The structural indicators were derived from the Swedish National Forest Inventory (NFI) and used as proxy for biodiversity potential. A biodiversity indicator score, based on the values of those indicators, was maximized. The model adjusted this score ensuring that all indicators were represented in the selection, and further also adjusted the influence of the indicators based on the subjective weightings. We evaluated the GP approach by comparing it to a simple linear programming (LP) formulation, only maximizing the indicator richness. In all cases the model was limited either by a budget or an area. The biodiversity potential in young forests are often neglected within present conservation policies, however, the proportion of selected forest under 15 years was relatively high in all our cost-effective cases, varying between 32% and 60% using the individual planners subjective weightings, compared to 80% when using a simple LP model. The proportion of selected forest over 100 years varied between 69% and 85% in the area-effective cases using the subjective weightings, compared to 80% when using a simple LP model. Middle-aged forest was not favored in any of the selections, although they make up a substantial part of the total area. We conclude that there are differences in how conservation planners prioritize the indicators, and depending on how specific biodiversity indicators are weighted the age distribution of the selected reserves differs. This demonstrates the importance of considering how to establish appropriate weightings. It is also important to consider the, at least in our case, substantial difference in how common the different indicators are to ensure that the weightings get their intended impact on the selections.

1. Introduction

The destruction, fragmentation and homogenization of natural landscapes have dramatically decreased biodiversity worldwide. Consequently, there is an urgent need to identify ways of mitigating diversity losses (Butchart et al., 2010). One common method of protecting and restoring biodiversity is to set aside areas for the maintenance and preservation of natural functions and processes in order to preserve viable populations of indigenous species (Schmitt et al., 2009).

A systematic approach to the process of finding and designing reserves has been introduced, known as systematic conservation planning (Margules and Pressey, 2000). Since the resources available for conservation do not cover all species in need of protection, effective prioritization is essential. To this end, various quantitative methods for designing optimal reserve networks have been developed over the last thirty years (Sarkar et al., 2006; Strager and Rosenberger, 2007; Williams et al., 2004). These site selection methods are generally based on the concepts of complementarity (Vane-Wright et al., 1991), irreplaceability (Pressey et al., 1994), and more recently, vulnerability (Wilson et al., 2005). If one assumes that there is spatial variation in (monetary) land values, the cost of achieving a given conservation goal by establishing a conservation area on a given area of land can be reduced by integrating the value of the selected land. Alternatively, by adopting an analogous approach, it may be possible to increase the level of biodiversity protection without affecting the cost incurred (Naidoo et al., 2006).

In addition, when designing and establishing reserves, it is essential to consider the preferences of the various stakeholders whose interests may be affected (Lahdelma et al., 2000; Moffett and Sarkar, 2006). Indeed, it is

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largely the preferences of the stakeholders that determine which of a given set of potential reserve networks is actually “the best”. There is a need for tools that can both predict the impact of the different designs on specific biodiversity targets and also account for the subjective preferences of decision makers (Regan et al., 2007). It is not generally straightforward to determine how much weight should be assigned to specific factors in situations of this sort where there are numerous variables that affect the outcome of the process. Thus the development and evaluation of weighting systems is an important research question (Polasky et al., 2001). Methods of this sort have been used to assign different weights to the protection of different species when designing conservation areas, as described by Arponen et al. (2005). The importance of considering different opinions during reserve selection has been emphasized in previous studies. Notably, Strager and Rosenberger (2006) investigated the spatial variation in the value assigned to specific priority areas by different stakeholders, while Regan et al. (2007) used input from a group of conservation specialists to identify factors that are important in assigning value to different aspects of biodiversity and in weighting these different factors. However, we are not aware of any studies on how the weighting of specific aspects of biodiversity affects the age composition of cost-effective forest reserve selections.

In a previous study, Lundström et al. (2011) sought to identify a cost-effective age composition for protected forest areas in boreal Sweden. Structural indicators that are considered important for many forest species, e.g. dead wood and large-diameter trees (Nilsson and Hedin, 2001; Stokland et al., 2012) were used as proxies for the biodiversity potential, and the character of the selected reserves were identified using a goal programming (GP) approach. A biodiversity indicator score, based on the measured values of these indicators was maximized. The design of the reserve selection model also adjusted this score ensuring that all of the indicators contributed to the resulting optimized solutions. The results indicated that the most cost-effective approach was to protect a large proportion of young forests, since they are relatively cheap but still contain the important structures. However, the model used by Lundström et al. (2011) did not account for the possibility that the variables considered might be of different relative importance. By incorporating the relative importance of each indicator for biodiversity in boreal forests based on the opinions of conservation planners we argue that the model would come closer to finding “the best” reserve network. Policy makers could then use the outcome when evaluating the character of future reserve network.

The main aim of the study described in this paper was to identify how the nature of the “optimal” conservation area network in any given situation varies depending on the relative importance assigned to different aspects of biodiversity. We focused on the age distribution since present conservation policy target almost only old-growth forests, which leads to a neglect of young forest biodiversity protection potential. Interviews were conducted with eight experts who work in practical reserve establishment to obtain information on their opinions regarding the relative importance of different aspects of biodiversity. The analytic hierarchy process (AHP) was applied to assign appropriate weightings to the different indicators used by Lundström et al. (2011). AHP is a well-known method that is used in multiple criteria decision analysis (MCDA) to handle the complex task of accounting for individual and collective preferences during processes such as systematic conservation planning (Ananda and Herath, 2009; Moffett and Sarkar, 2006). The classical way of solving reserve selection problems of this type is to use simple linear programming (LP) (Williams et al., 2004), with the goal of maximizing indicator richness. However, this approach does not account for the fact that there can be large differences between the indicators in terms of their commonality risking that a common indicator dominate and controls the selection just because it is common, and a rare indicator might not be selected at all. Neglecting this inequality could prevent the weights from having their intended impact, since if the common indicators will rule the selection the weights will not have any effect. We therefore wanted to investigate the implications of this neglect by comparing a GP model to a simple LP model.

2. Methods

2.1. Study area & data

The extended model was applied to the whole of boreal Sweden (Ahti et al., 1968). The boreal forest is relatively homogenous due to its low tree species diversity (Esseen et al., 1997); it is dominated by Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), with the main deciduous trees being the birches (*Betula pendula*

Table 1
List of biodiversity indicators, criteria for assigning points, and the normalization factors used in Case 12.

Indicator	100 points	50 points	0 points	Normfact[5]
Uneven age[1]	Uneven-aged	Fairly even-aged	Completely even-aged	19
Stand character[2]	Pristine		Normal	827
Tree layer[3]	Fully layered/several layers	Two layers	One layer/no layer	21
Ground structure[4]	Very uneven/fairly uneven	Fairly even	Very even	27
Large pine	>40 cm dbh	>30 cm dbh	Not present	79
Large spruce	>40 cm dbh	>30 cm dbh	Not present	118
Large birch	>40 cm dbh	>30 cm dbh	Not present	790
Large aspen	>40 cm dbh	>30 cm dbh	Not present	1890
Large deciduous tree (not birch or aspen)	>40 cm dbh	>30 cm dbh	Not present	3309
Dead conifer tree lying	Tree > 20 cm dbh		Not present	85
Dead deciduous tree lying	Tree > 20 cm dbh		Not present	340
Dead conifer tree standing	Tree > 20 cm dbh		Not present	160
Dead deciduous tree standing	Tree > 20 cm dbh		Not present	575
Presence of rowan	Present		Not present	32
Affected by water (moving water/spring/temporarily flooded)	Yes		No	606
Volume of dead wood	>20 m^3/ha	≤20 m3/ha[6]		0.03

[1] Completely even-aged: >95% of the volume within an age interval of 5 years, fairly even-aged: >80% of the volume within an age interval of 20 years. Remaining stands classed as uneven aged.
[2] Pristine character: presence of coarse (>25 cm diameter) dead wood and no trace of management actions during the last 25 years.
[3] Tree layer: group of trees amongst which the height is approximately the same, but their mean height differs from other layers. Fully layered: all diameter classes represented, the biggest tree > 20 cm in diameter, the number of stems increasing with increasing diameter class, and the volume density (relationship between the actual volume in the stand and the potential volume) > 0.5.
[4] Ground structure: Classification based on height and frequency of irregularities (rocks, small hills and holes) on the ground.
[5] Normalization factor based on the mean point over all areas.
[6] Normalized point according to the volume of dead wood/ha, from 0 to 100.

Roth. and *B. pubescens* Ehrh.), and aspen (*Populus tremula* L.) (Swedish Forest Agency, 2012).

The forest data used in this work were obtained from the Swedish National Forest Inventory (NFI) (Axelsson et al., 2010). The NFI is an annual survey of all land in Sweden that was initiated in 1923; its current systematic cluster design was established in 1983. It is conducted within a series of square tracts that are systematically distributed across Sweden. Within each tract, there is a series of circular plots (with radius 7 or 10 m) that runs along the tract's boundary. Approximately 11 000 plots are surveyed each year (Anon, 2007). This work examined data gathered between 2003 and 2007 from plots within the study area that are located on productive forest land that is outside existing reserves. In total, 17 599 plots satisfied these criteria.

In order to establish proxies for assessing the biodiversity potential associated with a given plan, we considered 16 structure-based indicators that are measured in the NFI surveys (Table 1). The structural indicators were selected based on the substrate types that are considered important for a majority of forest species (Ferris and Humphrey, 1999; Lindenmayer et al., 2000; Spanos and Feest, 2007). We therefore assumed that sites with high values for these indicators would provide habitats that might foster high levels of species diversity and provide shelter for many rare species. The perceived biodiversity value of each indicator was ranked on a scale that ranged from 0 to 100 points; however most indicators were limited to 100, 50 or 0 points (Table 1). In this paper we use value when referring to the measured value in the NFI survey, point when referring to the assigned value based on the measured value, and score when the points are added together.

The opportunity cost of establishing each proposed set of conservation areas, i.e. the economic value of the plots involved, was estimated based on the net present value (NPV) i.e. the sum of the expected future income derived from timber harvesting and the costs of harvesting, discounted back to the present day. Opportunity costs were estimated using the PlanWise application from the Heureka system, a recently developed planning system for multiple-use forestry (Wikström et al., 2011) that is used by private forest companies, public agencies and in research. PlanWise was used to simulate up to 50 different treatment schedules (a sequence if treatments, e.g., regeneration, thinning clearcutting or doing nothing, for a planning unit from period 1 to the end of the planning horizon) for each plot, and the NPV values for each schedule were then estimated using a 3% interest rate. The highest of these estimated NPVs was then taken to represent the opportunity cost for that plot. The costs and benefits for each possible action were based on a timber price list (the default Heureka list for northern Sweden). In cases where all of the estimated NPVs were negative, the NPV was set to zero since we assumed that in such cases the owner would choose to leave the plot unmanaged.

The NFI plots were aggregated into 112 larger plots (each with an area of 25 000 km^2. 292 of the NFI plots located on the edges of the study area were excluded because it was decided that each large plot should contain at least 30 NFI plots, and there was no way to accommodate the excluded plots in an appropriate large plot (Fig. 1). The forest data in each large plot were classified into one of five age classes (0–14, 15–39, 40–69, 70–99 and ≥100 years). The total area of land represented in each age class was 2.4, 3.5, 3.0, 2.0 and 3.5 million ha, respectively. Some classes covered a wider range of ages than others because tree retention practices i.e. retaining living and dead trees during final harvest (Lindenmayer and Franklin, 2003), were introduced about 15 years prior to the period covered in the study (i.e. 2003–2007). This practice has affected the structural composition of the forest (Kruys et al., 2013) and we therefore wanted to have a single class covering that period. Rotation periods of 100 years are typically used in boreal forests managed with the clear-cutting system, and the choice of break point for the highest age category was informed by this fact. The points of the biodiversity indicators for each plot within a large plot were summed and averaged to give a per-hectare biodiversity indicator score for that large plot. This was done for each indicator and age class in each large plot, with the exception of the volume of dead wood, which was determined based on NFI measurements of the actual volume of dead wood per hectare within each large plot. It was assumed that this would yield a more accurate point than could be obtained based on the points from the NFI plots. It has been suggested that a dead wood content of 20 m^3 ha-1 represents a threshold value that permits the survival of various saproxylic species (Martikainen et al., 2000; Penttilä, 2004). Therefore, large plots containing more than 20 m^3 ha-1 dead wood were given 100 points for this indicator; large plots with less dead wood were given normalized points (calculated by dividing their measured dead wood content by the reference value of 20 m^3 ha-1 and multiplying by 100) of 0–100 according to their dead wood contents.

2.2. Subjective weights

To establish weightings for the different indicators, we interviewed eight conservation planners who are employed by the county administrative boards in boreal Sweden (Värmland, Örebro, Dalarna, Gävleborg, Jämtland, Västernorrland, Västerbotten and Norrbotten) and who work on the establishment of conservation areas. In Sweden, the establishment and maintenance of conservation areas is the responsibility of county administrative boards and the municipalities. Most of the interviews were conducted in the autumn of 2010, but one interview

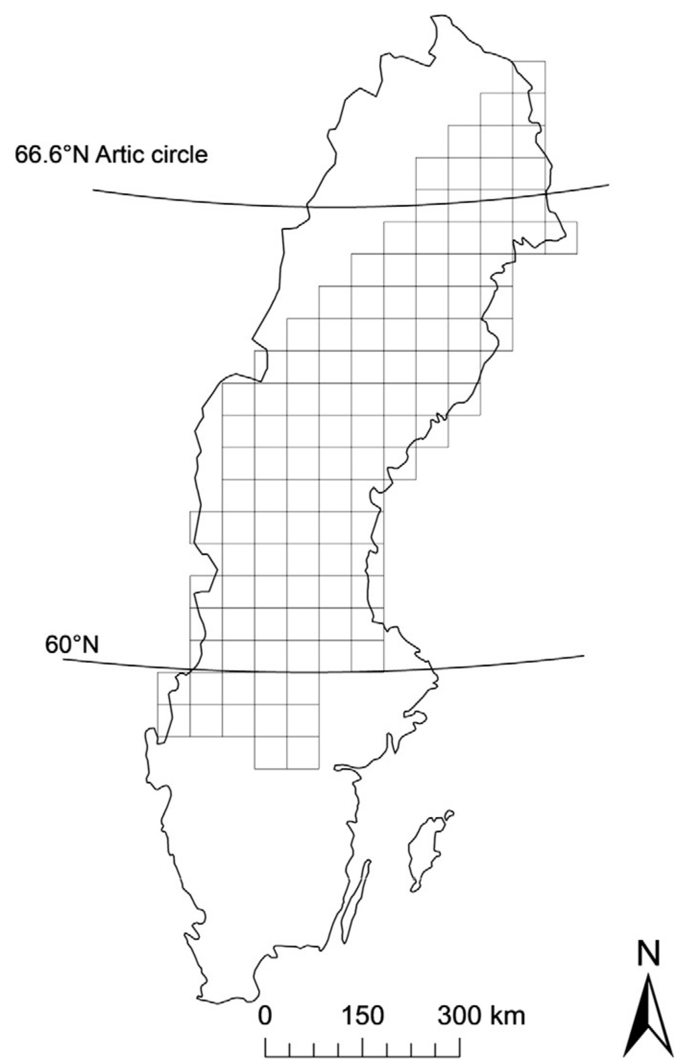

Fig. 1. Map of the study area. The NFI-plots are systematically distributed within Sweden. Our study focused on the boreal zone (the area within the squares). NFI plots were grouped into larger plots (squares with area 25 000 km^2).

was conducted in the spring of 2012. All of the interviewed planners had been working on reserve establishment for at least 4 years. All of the interviews were conducted face-to-face, at the offices of the administrative county boards. Each session started with a short description of the study's purpose and objectives, followed by an explanation of how an inquiry form should be filled in.

The inquiry form was based on the pairwise comparisons procedure of the AHP (Saaty, 1990). The AHP is one of the most well-known techniques for obtaining and quantifying preferences, and it has been used in a number of forest planning applications over the last twenty years (Ananda and Herath, 2009; Diaz-Balteiro and Romero, 2008). Numerous detailed descriptions of the AHP have been published elsewhere (Ananda and Herath, 2009; Ho, 2008; Vaidya and Kumar, 2006). The standard AHP technique for determining preferences was applied in our study using the following four-step procedure:

1. In the first step, prior to the interviews, the indicators were arranged in a hierarchy that defined the relationships between them. This hierarchy was shown to the planners to give them an overview of these relationships (Fig. 2).
2. In the second step, the planners were asked to perform a series of pairwise comparisons among the elements of the hierarchy in order to establish their relative priority. All of these comparisons were made using the standard nine-point ratio scale to determine the planner's strength of preference for one element over another. In this way, weightings were obtained both for groups of indicators and for the actual indicators. The highest level of the hierarchy consisted of one indicator (stand character) and three indicator groups (stand structure, individual characteristics, and hydrology/topography). Therefore, six pairwise comparisons were made at the highest level of the hierarchy. This process was repeated until all elements on the same level of the hierarchy and belonging to the same branch had been compared, giving a total of 23 comparisons. The planners were asked to fill out the AHP inquiry form in order to record their opinions.
3. In the third step the weights of the indicators were calculated (Table 4). This was done after the interviews. In standard AHP, weightings are obtained by normalizing the values of the eigenvector that corresponds to the maximum eigenvalue for each comparison matrix, i.e. the outcome on each level. Vector calculations were performed using the PlanEval application of the Heureka package. We considered both the individual weightings assigned by each planner and the arithmetic mean of all eight planners' weightings.
4. Finally, in step 4, the consistencies of the judgments were checked. This was done by determining the consistency ratio (CR) for each planner and hierarchical level (Saaty, 1990) (the CRs can be found in Appendix).

A CR of 0.1 or less is considered acceptable in most studies (Saaty, 1990). In cases where the level of inconsistency exceeds this limit, at least three options are available: one can ask if the planner could reconsider their judgments, the analyst can refine the original judgments and present the refined evaluations to the planner for approval, or one can simply accept an elevated CR threshold. In this case study, the CR values for the planners' responses were higher than 0.1 in several cases (see Appendix). However there was no opportunity to work iteratively with the planners to improve the consistency of their evaluations. Therefore, the judgments of all planners were accepted even if the resulting CR values were greater than 0.1. That is to say, we accepted that some of the planners were moderately inconsistent in their prioritizations of different indicators.

2.3. Model description

The model used to identify optimal combinations of forest ages when establishing nature reserves in this work was based on that described previously by Lundström et al. (2011). In this model, the biodiversity potential is measured as the score from a range of biodiversity indicators (Table 1). In the current study, the model is extended to accommodate individual weightings for the different indicators. This makes it possible to account for the preferences and priorities of individual decision makers. The objective of the model is to maximize the biodiversity potential within the designated reserve area by considering all of the indicators simultaneously. To account for the large variation in

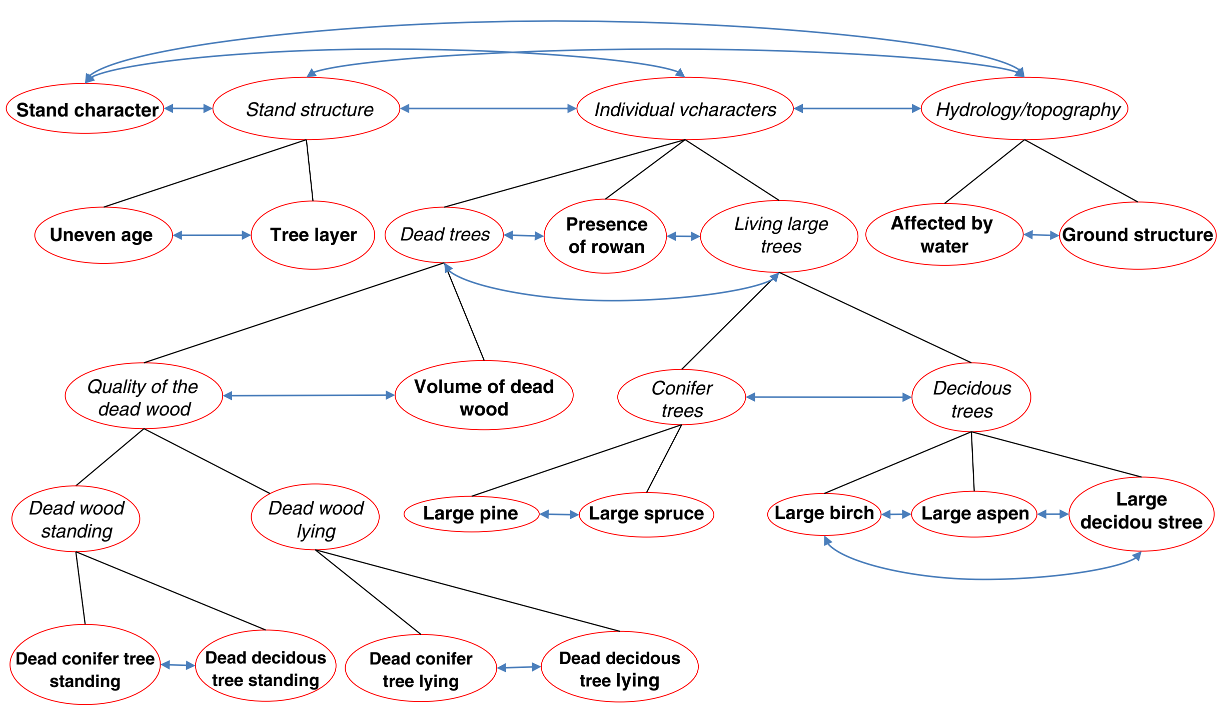

Fig. 2. The hierarchical structure of the elements, the indicators to be weighted are shown in bold, the groupings of indicators are shown in italics, and pairwise comparisons are indicated with blue arrows.

Table 2
Parameters and decision variable for the model.

Notation	Description
Parameters	
I	Set of large plots ($i = 1,\ldots,n$)
T	Set of age classes ($t = 1,\ldots,m$)
E	Set of biodiversity indicators ($e = 1,\ldots,o$)
w_e	Weight of biodiversity indicator e
w_{AHPe}	Subjective AHP weight of biodiversity indicator e
p_{ite}	Point of biodiversity indicator e in plot i and age class t
a_{it}	Area (ha) of plot i in age class t
c_{it}	Cost ha^{-1} of plot i and age class t
q	maximum proportion that can be selected
b	Available budget (SEK)
f_t	Minimum proportion that has to be selected in age class t
Decision variable:	
x_{it}	Area (ha) selected in plot i and age class t

points for different indicators (and thus to prevent certain common indicators from dominating the results), a GP approach was used. This involves a two-phase process: in the first phase, the maximum value for each indicator is identified and selected as the goal value. In the second phase, a solution is identified that comes as close as possible to the goal values for each indicator, considering the relative importance of the indicators.

The LP problem used in the first phase can be formulated as follows (see Table 2 for parameters and decision variables):

$$[P1]\ \max z = \sum_{i \in I}\sum_{t \in T}\sum_{e \in E} w_e p_{ite} x_{it} \quad (1)$$

Subject to:

$$\sum_{i \in I}\sum_{t \in T} c_{it} x_{it} \le b \quad (2)$$

$$\sum_{i \in I}\sum_{t \in T} x_{it} \le q \sum_{i \in I}\sum_{t \in T} a_{it} \quad (3)$$

$$x_{it} \le a_{it}, \forall i \in I, t \in T \quad (4)$$

$$x_{it} \ge o, \forall i \in I, t \in T \quad (5)$$

The objective (Eq. 1) is to maximize the sum of the points from the biodiversity indicators in the selected areas (the biodiversity indicator score). The budget constraint (2) limits the total cost (b) of the selected areas. The area constraint (3) prevents the selected area from exceeding a certain proportion (q) of the total area. The constraint specified by Eq. (4) ensures that the selected area is smaller than the total area. Finally statement (5) ensures that the decision variables are positive.

Goals are established by solving problem [P1] for each indicator in isolation, i.e. by setting w_e to 1 for the targeted indicator and 0 for all other indicators. Those goal values are denoted z_e and vary substantially between the indicators (for example, the goal value for the “volume of dead wood” indicator was over 25,000 times greater than that for the “large deciduous trees” indicator), which is why a GP approach was needed.

The second phase involves a search for a solution in which the value for each indicator is as close as possible to its goal value while accounting for the relative importance of each indicator (w_{AHPe}).

$$[P2]\ \min y = \sum_{e \in E} w_{AHPe} \left(\left(z_e - \sum_{i \in I}\sum_{t \in T} p_{ite} x_{it} \right) / z_e \right)^2 \quad (6)$$

The second objective (Eq. 6) is thus to minimize the squared difference between the goal and the biodiversity indicator score for

Table 3
List of the models tested in the study and definitions of the restrictions. The AHP weightings were included in the objective function in all cases except 10–12.

			Budget (2)	Area (3)	Max area (4)	Non-negative (8)
		Weights				
1	A	Mean AHP	x		x	x
	B	weights		x	x	x
		(base case)				
2	A	Stakeholder 1	x		x	x
	B			x	x	x
3	A	Stakeholder 2	x		x	x
	B			x	x	x
4	A	Stakeholder 3	x		x	x
	B			x	x	x
5	A	Stakeholder 4	x		x	x
	B			x	x	x
6	A	Stakeholder 5	x		x	x
	B			x	x	x
7	A	Stakeholder 6	x		x	x
	B			x	x	x
8	A	Stakeholder 7	x		x	x
	B			x	x	x
9	A	Stakeholder 8	x		x	x
	B			x	x	x
		Objective functions				
10	A	GP	x		x	x
	B	(AHP weights)		x	x	x
11	A	Only LP	x		x	x
	B			x	x	x
12	A	LP + norm.	x		x	x
	B	factor		x	x	x
13	A	LP + AHP	x		x	x
	B	weights		x	x	x

each indicator. The relative importance of each indicator (w_{AHPe}) is incorporated into Eq. (6) as a factor governing the extent to which each indicator contributes to the final solution. The deviation is measured as a percentage, so all goal values contribute equally regardless of their absolute magnitude. If the output in phase 2 (y) is 0, the identified solution satisfies the goal values for all of the indicators. Problem [P2] is convex (Lundgren et al., 2010) and so the method is guaranteed to identify a globally optimal solution.

2.4. Case description

We investigated how variation in individual preferences affected the nature of the selected reserves and the consequences of not considering the fact that some indicators are found in many sites while others are far less common in 26 cases. Of these, 13 were subject to budgetary constraints while the other 13 were subject to constraints on the total area of land that could be allocated. The two base cases (see Table 3) were Cases 1 a (subject to a budgetary constraint) and 1 b (subject to an area constraint); in both of these cases, the weightings assigned to individual biodiversity indicators were the mean subjective AHP weightings established by considering the responses of all of the interviewed planners. The budgetary limit was set at 10 billion SEK, which was considered to be a realistic sum given the prevailing political climate in Sweden; for comparative purposes, 6 billion SEK was allocated for the establishment of conservation areas between 1998 and 2008 (Swedish Government, 2009). The area limit was set at 4% of the country's boreal forests, since that scenario gave approximately the same biodiversity indicator score as was achieved in the base case for the scenario with a budgetary constraint. Cases 2–9 are alternative scenarios in which the weightings assigned by individual planners were used to specify the values of *wAHPe* rather than the average weightings for all of the interviewed planners.

Four different versions of the model's objective formulation were tested. In Case 10 the AHP weightings were disregarded (i.e. *wAHPe* was removed from Eq. (9)). In Case 11, a simple LP objective function was used, i.e. the selection was made using only phase 1

Table 4
The stakeholders' individual weightings and the mean weightings for the biodiversity indicators (weights multiplied by 100), obtained from the AHP questionnaires.

Indicator	1	2	3	4	5	6	7	8	Mean
Uneven age	27.8	48.1	11.4	26.6	4.2	18.3	10.0	6.5	19.0
Stand character	13.0	27.0	67.0	30.0	60.0	67.0	62.0	42.0	46.0
Tree layer	9.3	9.9	1.7	5.4	0.9	3.7	2.0	6.5	5.0
Ground structure	1.2	2.0	2.0	0.9	3.0	2.5	0.5	1.5	1.9
Large pine	2.5	0.4	0.8	0.9	2.1	0.6	3.0	18.2	2.6
Large spruce	0.5	0.4	0.3	0.2	0.7	0.1	0.6	3.7	0.8
Large birch	0.8	0.6	0.9	0.3	0.9	0.1	0.9	2.6	1.2
Large aspen	4.1	0.8	2.0	2.4	6.9	0.3	5.3	1.4	3.1
Large deciduous tree	4.1	1.2	0.5	0.7	5.7	0.3	4.8	0.5	2.1
Dead conifer tree lying	9.2	1.2	0.5	1.1	0.8	1.6	0.6	7.1	1.3
Dead deciduous tree lying	9.2	0.4	1.5	1.1	2.4	0.3	1.9	2.4	2.7
Dead conifer tree standing	1.5	0.8	1.5	0.2	0.8	1.0	0.4	1.0	2.7
Dead deciduous tree standing	4.6	0.8	4.4	0.6	2.4	1.0	2.1	1.0	2.6
Presence of rowan	3.0	1.2	0.9	4.5	3.9	0.3	1.4	2.5	2.3
Affected by water	5.8	2.0	2.0	4.2	3.0	2.5	3.5	1.5	3.2
Volume of dead wood	3.6	3.1	1.6	20.0	1.3	0.4	1.7	1.3	3.8

[P1] from the base model and the same weighting (w_e) was assigned to all indicators. We then simply maximized the total biodiversity indicator score for the selected areas. Case 12 represented a development of the simple LP model in which a normalization factor (n_e) was added to each indicator in order to increase the value assigned to rare indicators while decreasing the influence of common ones. This is an alternative way of objectively accounting for the large differences in total points between the indicators, and the objective function was then formulated as follows:

$$[P1]\ \max z = \sum_{i \in I} \sum_{t \in T} \sum_{e \in E} n_e p_{ite} x_{it} \tag{1b}$$

Here, n_e was calculated as the mean point for each indicator, normalized to 1. In Case 13, only phase 1 was active and w_e was replaced with $wAHPe$. In Cases 10 a, 11 a,12 a and 13 a only the budgetary constraint (Eq. 2) was imposed, whereas in Cases 10 b, 11 b, 12 b and 13 b only the area restriction (Eq. 3) was imposed. In all of these cases, these restrictions were imposed along with those specified in Eqs. (4) and (5) (Table 3).

The models were formulated in the modeling language AMPL and solved using the CPLEX 11.2 software package.

3. Results

3.1. Preferences

The eight conservation planners valued the different indicators differently. In some cases, the importance assigned to specific indicators by different planners differed by more than a factor of ten — notably, for the volume of dead wood and uneven age indicators (Table 4). Uneven age and stand character were considered to be the most important indicators by most of the planners, but the priority assigned to these indicators differed.

3.2. Forest age distribution

There were some notable differences between the forest age distributions within the optimal reserve areas identified using the mean weightings (Case 1) and those identified using the weightings specified by individual planners (Cases 2–9). The proportion of the youngest age class (<15 years) in the selected area varied between 32% and 60% in the budget-constrained scenarios, standing at 46% in the base case (Fig. 3a). Similarly, the proportion of the oldest age class (>100 years) varied between 69% and 85% in the area-constrained scenarios, standing at 77% in the base case (Fig. 3b). Middle-aged forests, especially those in the 41–70 age group, were not favored in any of the selections, accounting for 1.3% of the selected area in Case 1 a and 5.1% of the selected area in Case 1 b. However, this age class and the oldest age class together accounted for the greatest total area within the selected regions.

There were also notable differences in the age distributions of the forest selected using different objective functions. However, the simple LP model (Case 11) and the simple LP model with AHP weightings (Case 13) were almost identical. In the budget-constrained scenarios, young forests (<15 years) accounted for almost 80% of the total area when using the GP model with equal weightings (Case 10 a) or the LP model with normalization factor (Case 12 a), whereas such forests accounted for only 46% of the total area in the base case (1 a) (Fig. 5). Old forests (>100 years) accounted for almost 80% of the total selected area in the base area-constrained scenario (Case 1 b) and the simple LP case with or without AHP weightings (Case 11 b and 13 b). However, in the GP case without weightings, and when using LP with a normalization factor (Cases 10 b and 12 b), old forests accounted for only around 50% of the total area (Fig. 5).

3.3. The importance of indicator weightings

In the first stage of the GP model, each of the 16 indicators is assigned a maximal value (the goal value) appropriate for the defined constraints in the base case (a budgetary limit of 10 billion SEK in the budget-constrained scenario and an area limit of 4% in the area-constrained scenario). When comparing the models with different objective functions (Cases 1, 10–13), the most common indicator (the volume of dead wood) dominated the selection made using the simple LP model with or without AHP weightings (Cases 11 and 13). The inclusion of a normalization factor (Case 12), reduced the dominance of this indicator and increased the importance of less common indicators such as large aspen, in both the budget- and the area-constrained cases (Fig. 4 a and b).

The outcomes obtained when using a normalization factor were quite similar to those achieved with the GP model with equal weighting on all indicators (Case 10); the most notable differences related to the dead fallen deciduous trees indicator in the budget-constrained scenario (Fig. 4a) and the large living deciduous trees indicators in the area-constrained scenario (Fig. 4b). In the base case (Case 1), the values achieved for indicators with high weightings were notably higher than those achieved using the GP model with equal weighting on all indicators (Case 10). For example, the value for the “uneven age” indicator (weighting = 0.19) in the conservation area selected in the base case was 45% greater than that for the area selected using the model with equal weightings in the budget-constrained scenario (Fig. 4a). Similarly, the value of the “stand character” indicator (weighting = 0.46) in the base case was 119% greater than that achieved with the model with equal weightings in the area-constrained scenario (Fig. 4b).

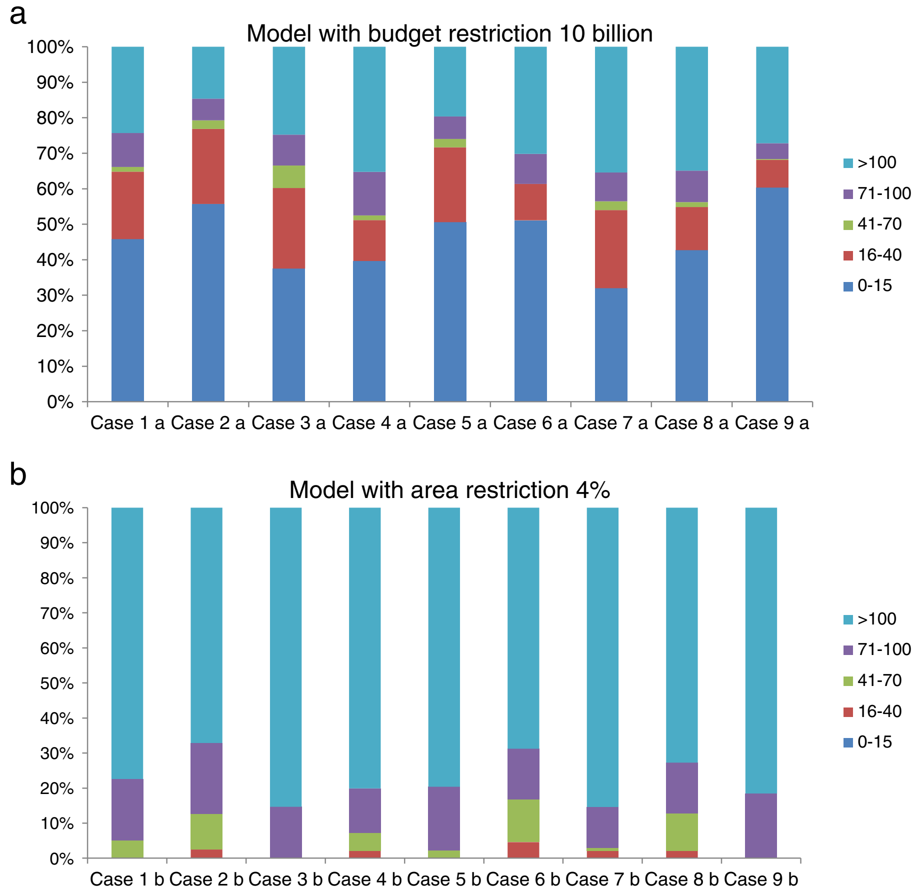

Fig. 3. Optimal age distributions given different preferences (based on the AHP questionnaire) obtained using a budget-constrained (a) and an area-constrained (b) GP model. Case 1 is the base case, in which the AHP weightings are the means of all 8 stakeholders' weightings. In Cases 2–9, the AHP weightings used in the model are those provided by a specific individual stakeholder.

Indicators with low weightings took lower values in the base case than they did when using the model with equal weightings. For example, the value for the "large birch" indicator (weighting = 0.012) was 50% lower in the budget-constrained scenario with the AHP weighted GP model (Fig. 4a) and the value for the "large aspen" indicator (weighting = 0.031) was 39% lower in the area-constrained scenario (Fig. 4b). The geographical distribution also varied depending on if subjective preferences were considered or not (Case 1 vs. Case 10), and also compared to the simple LP variant (Case 11) (Fig. 6).

4. Discussion

The designation of reserves and conservation areas involves making decisions, which are always made based on a combination of objective facts and subjective preferences regarding the relative importance of different aspects of biodiversity. In this work, we investigated how the nature of the "optimal" reserve in any given case will vary depending on the relative importance assigned to different structural biodiversity indicators. The results presented herein demonstrate that the incorporation of the preferences from conservation planners in reserve selection models can profoundly affect the selection, and that when there are large differences in how common these preference-based indicators are, it is necessary to use a method that can accommodate such variation.

In this study conservation planners have been used to decide subjective weightings of the indicators, however, they only represent a small part of all stakeholders affected by reserve establishment. Our model focuses only on the objective biodiversity and the weighting in our case is used to identify a more accurate measure of biodiversity potential based on different expert opinions.

There were differences between the eight conservation planners in how they prioritized the indicators, but generally they preferred indicators that related primarily to older forests. We also observed large differences in the contributions of the different indicators to the total score in the different cases. Common indicators dominated the selection process if the inequalities in the scores for each indicator were not accounted for by using the GP approach or by applying a normalization factor. Hence, when we added the weightings given by the planners to the simple LP model the selection did not change, since the effect of common indicator dominance was so strong. In general, models that focus exclusively on maximizing the total biodiversity indicator score (such as that used in Cases 11 and 13) do not assign sufficient weight to rare indicators. We therefore recommend the use of models that consider a possible unequal representation of the different indicators (such as those used in Cases 1, 10, and 12), at least in situations of the type considered in this work.

Old forests dominate existing reserves in boreal Sweden: 76% of the protected forests are over 100 years in age and only 1.5% is below 15 years of age (NFI data). In the budget-constrained scenarios considered in this work, the youngest age class was dominant in the selected areas. However, this trend was less pronounced in the base case than in the selections established without using AHP weightings (Fig. 4). The fact that changing the weighting of the indicators has such a profound impact on the age composition of the selected area clearly demonstrates the importance of taking care when establishing weightings.

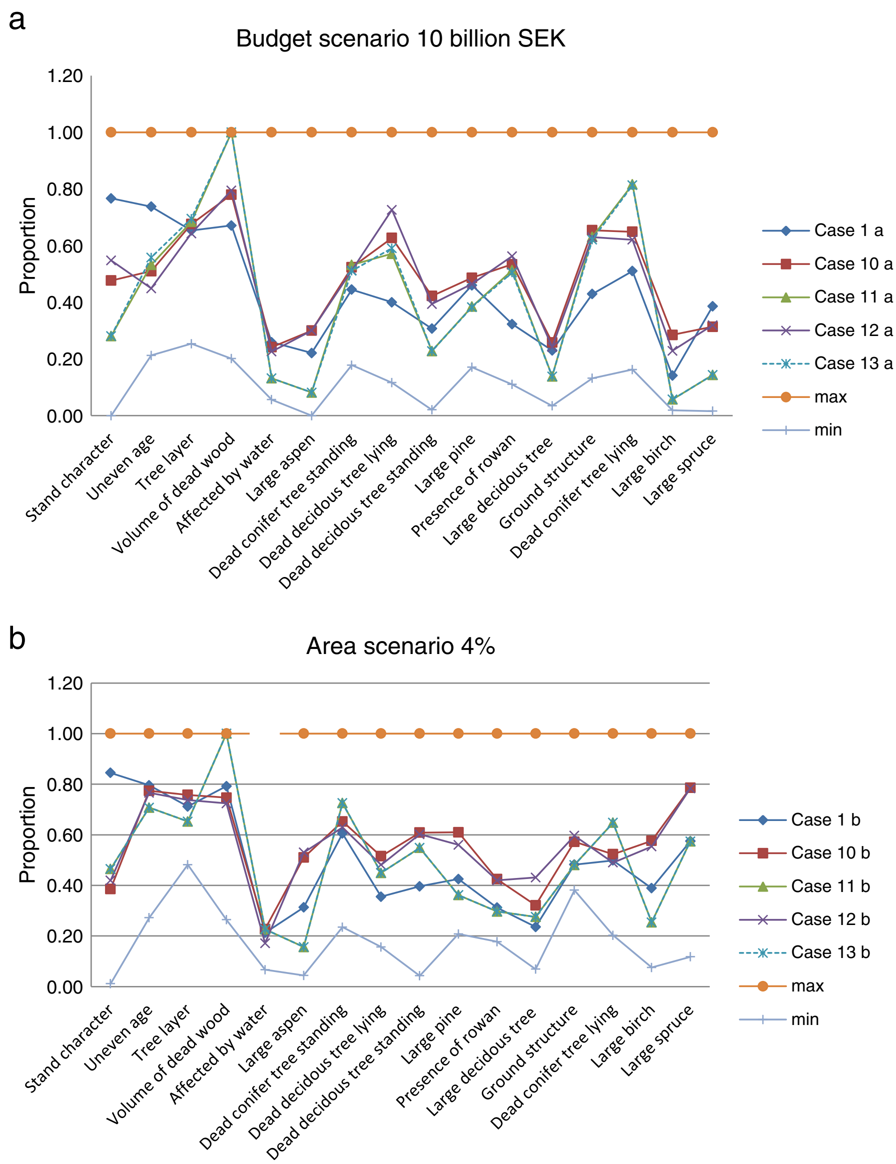

Fig. 4. Each indicator's contribution to the total biodiversity indicator score in the budget- (a) and area-constrained (b) scenarios. The indicators are arranged by degree of importance: the indicator with the highest mean AHP weight is placed furthest to the left and indicators decrease in weight when moving rightwards. The goal value (max) is established in the first stage of the GP model, during which the targeted indicator is assigned a weight of 1 and all others are given a weight of 0. The minimal value is the lowest possible value that the indicator can take when another indicator has a weight of 1. Case 1 is the base case (GP with AHP weights), Case 10 is GP with the same weight on all indicators, Case 11 uses only the first phase in the GP formulation, a LP formulation maximizing the biodiversity indicator score, Case 12 is the LP model with a normalization factor and Case 13 is the LP model with the AHP weights.

The criteria and associated factors used to estimate biodiversity values are often established by a single person or a small group of people and thus depend strongly on the knowledge and experiences of those individuals. In order to create a sound basis for decision-making, it is essential that the selection criteria and weightings are established by a group of knowledgeable individuals (Regan et al., 2007). Since different planners prioritize differently, our model can be used when developing a new unified conservation policy combining the knowledge from several planners.

We used AHP to decide weightings even if there are other alternative methods that could also be suitable, e.g. MAVT and modified AHP (Moffett and Sarkar, 2006). Despite some disadvantages, AHP is widely used in other studies concerning forestry and natural resource management (Mendoza and Martins, 2006).

The AHP is assumed to be a rather straightforward technique, the pairwise comparison is also assumed to simplify the weighting for the planners since it is easier to express ones preferences when only two criteria are compared simultaneously. The hierarchical structure also allows planners to focus on the specific criteria and sub-criteria when allocating weights. On the other hand different hierarchical structure may lead to different weightings and criteria with many sub-criteria tend to get a higher weight than criteria with few sub-criteria (Stillwell et al., 1987). One solution to this problem is to present the hierarchy with another criteria order. However, this was not possible in this study. Further, to be able to define a hierarchical problem in a good way the set of elements should be essential, controllable, complete, measurable, operational, decomposable, nonredundant, concise and understandable (Keeney, 1992). We have some problems with double counting among the indicators; the definition of forest continuity includes dead wood and uneven age. However, we argue that forest continuity is such an important indicator when identifying forest with high conservation value, and so is dead wood and uneven age even if it is not in a continuity forest that we need all three.

One problem with AHP is that the method allows the person making the pairwise comparisons to be inconsistent in their weightings within each level of the hierarchy (Barzilai, 1997; Dyer, 1990). The risk when

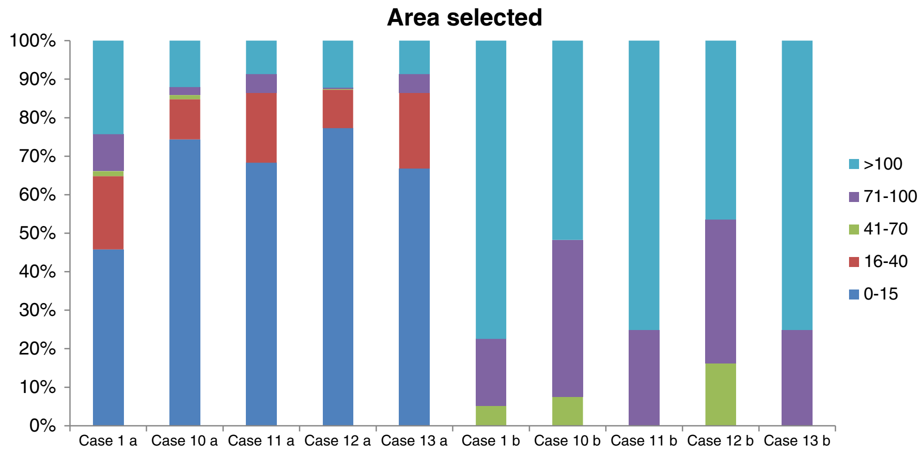

Fig. 5. Optimal age distribution under different objective functions. Case 1 is the base case (GP with AHP weights), Case 10 is GP with the same weight on all indicators, Case 11 uses only the first phase, a LP formulation maximizing the biodiversity indicator score, Case 12 uses the LP model with a normalization factor and Case 13 uses the LP model with the AHP weights. The “a” versions are obtained using a budget-constrained model (10 billion SEK) while the “b” versions are obtained using an area-constrained model (4% of the total area).

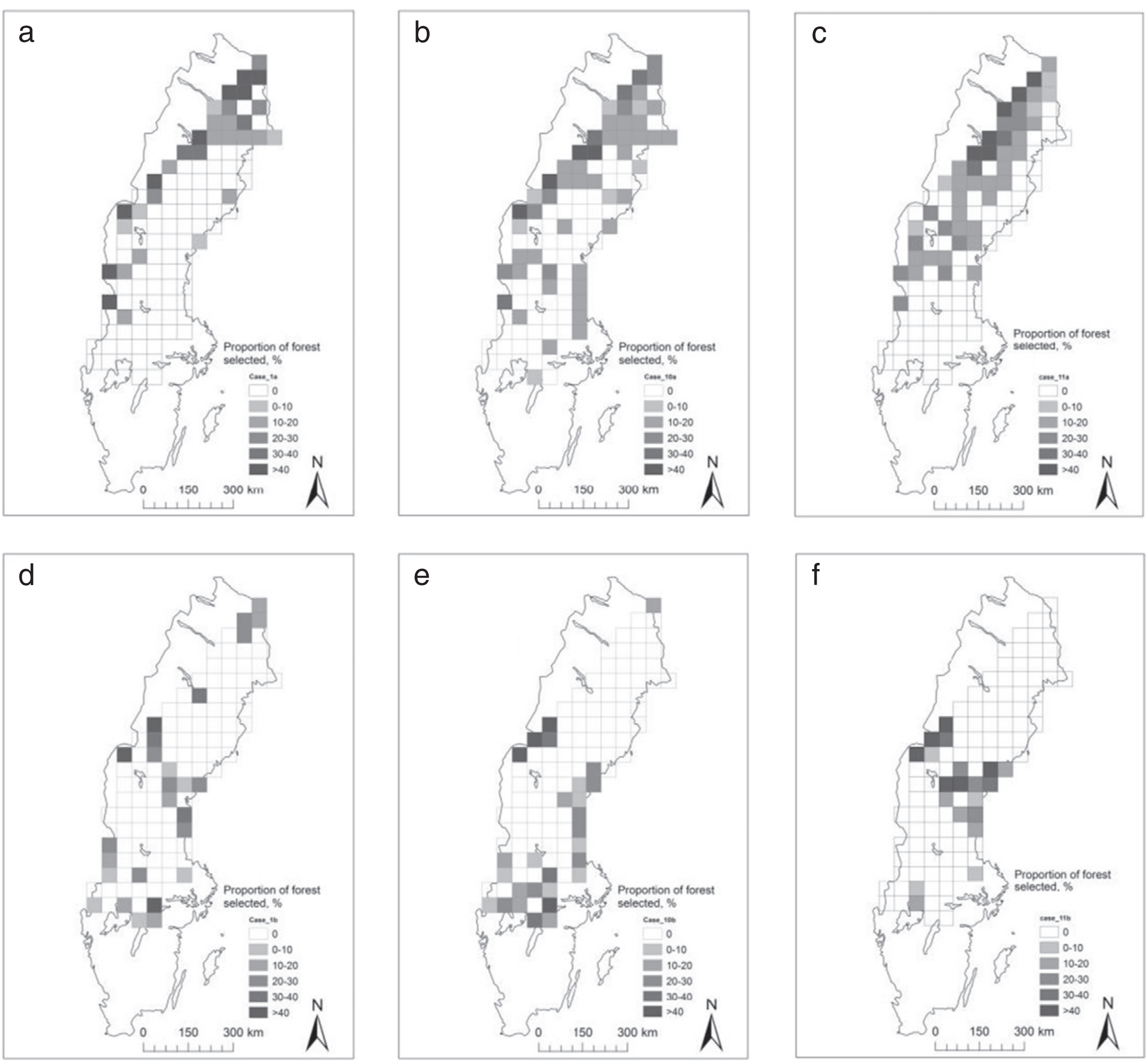

Fig. 6. Geographical distribution of the selected area under a 10 billion SEK budget constraint in the base case using subjective weights (a), Case 10 a without weights (b) and Case 11 a using a simple LP formulation (c), and the geographical distribution of the selected area under a 4% area constraint in the base case (d), Case 10 b (e) and Case 11 b (f).

having high inconsistencies is that the weightings do not coincide with the true preferences of the planner. We encountered inconsistencies in some of the planners' answers. Saaty (1990) argues that the best solution to this problem is to have a discussion with the decision makers and thereby increase the consistency of their responses. This was not an option for us. Numerical methods for reducing inconsistencies have been developed (Cao et al., 2008). However, an experiment conducted by Linares (2009) suggests that the removal of inconsistencies does not increase the decision makers' satisfaction with the outcome of the process. Therefore, we chose to accept the inconsistencies in the planners' responses, and believe that by doing so, we are more likely to accurately represent the planners' "true" preferences than would be the case if we manipulated the data.

We solicited feedback from some of the planners concerning their opinions about the selections made using their weightings. They did not disagree with their own weightings, but pointed out that there was some room for differences in the interpretation of the indicators' meanings, especially for indicators such as "stand character" and "uneven age". Errors arising from such differences could be reduced if the planners were allowed to discuss the questionnaire with one-another rather than filling it out individually. Some skepticism was expressed regarding the high proportion of young forest in the selected areas, since this was considered to be inconsistent with the traditional age profile of a reserve network. The general consensus was that natural young forests have high biological value and considerable biodiversity potential, but that the few old-growth remnants should be prioritized.

In the study a common arithmetic mean was used to aggregate the preferences of the planners. Other approaches could also have been used, such as geometric mean or weighted arithmetic means (Ramanathan and Ganesh, 1994) in which the weightings could have been determined for example by the size of the area managed by each represented administrative county board, or by how extreme a given planner's weightings were relative to those of their peers. A third possibility would be to aggregate the preferences based on the degree of consensus among the planners (Nordström et al., 2009).

We have been searching for general reserve network characteristics that can be used when evaluating reserve selection policies, and not actual reserve locations. Since we have used data from NFI plots, which are small and not representative as reserves by their own, we cannot make such fine scale analyses. Instead, the NFI plots are used as random samples representing larger areas. This is why we chose to aggregate the plots into larger plots and use a continuous instead of a binary decision variable in the reserve selection models.

Several studies have shown that environmental variables can be used as surrogates for species richness (Bonn and Gaston, 2005; Faith, 2003; Sarkar et al., 2005) although their usefulness has been questioned (Araújo et al., 2001). Since identical structures could provide habitats for different species at different stages of forest succession, it would be interesting to test how the selected age composition would vary if the goal was to maximize species richness rather than structural diversity. However, even if one were to measure species richness, it would still only be a surrogate for a hypothetical "general diversity" variable (Sarkar and Margules, 2002).

Negative impacts on biodiversity from humans are increasing and climate change will fundamentally alter future conditions (Pressey et al., 2007; Araujo et al., 2004). Thus, the areas selected in this model might not be the same as the areas in most need of long-term protection. A future development of the model would be to consider also the possibility that the area could lose its high protection value. At present, reserve selection is primarily based on the current situation within the forest. However, it would be interesting to investigate what would happen if decisions were made in a way that also accounted for the selected area's future potential. This could potentially results in a more cost-effective selection that also accounted for the future ecological value of different forests.

5. Conclusions

Our study clearly shows that weightings assigned to biodiversity indicators when selecting forest reserves may strongly affect the age composition of the selected areas. It is therefore important to use a reserve selection model that can consider different weightings. It is also important that the model can compensate for the often large variation in abundance among indicators to ensure that each indicator's influence reflects the weightings given by planners.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.forpol.2013.12.007.

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