

Examining alternative landscape metrics in ecological forest planning: a case for capercaillie in Catalonia

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Abstract

This study examined the performance of four different landscape metrics in a landscape ecological forest planning situation in Catalonia: (1) proportion of suitable habitat (non-spatial) (%H); (2) spatial autocorrelation; (3) the proportion of habitat-habitat boundary of the total compartment boundary (H-H) and (4) the proportion of habitat-non-habitat boundary (H-nonH). They were analysed in a case study problem that aimed at the maintenance and improvement of capercaillie habitats in two simulated forests of 14,400 hectares consisting mainly of *Pinus uncinata*, *P. sylvestris* and *P. nigra* stands. The habitats were determined by using a stand-level habitat suitability index (HSI). Stands in which the HSI exceed a specified threshold value were considered as habitats. Then, four different planning problems were formulated to test the four landscape metrics as one of the management objectives. The objective functions of the problems were written in the form of an additive utility model, and the problems were solved using heuristic optimization techniques. Before this, five different heuristic optimization techniques: random ascent; Hero, simulated annealing (SA), tabu search and genetic algorithms (GA), were compared in a non-spatial and a spatial planning problem. Based on these comparisons, GA was selected for solving the spatial planning problems while SA was used for non-spatial problems. The spatial pattern of habitat patches was comparable when using the %H, H-H or spatial autocorrelation as a management objective. However, the limitations of using the non-spatial %H objective were clear in the second forest landscape with lacking trends in forest features. H-H and spatial autocorrelation yielded a more clustered landscape with larger habitat patches. The largest proportions of habitat and habitat-habitat boundaries were created when using the H-H as the ecological management objective. The use of spatial autocorrelation as a management objective resulted in a smaller habitat area and shorter habitat-habitat boundary than when %H and H-H were used as objectives, but the proportion of large habitat patches was rather high. H-H was very suitable for connecting habitat patches. When H-nonH was used as the ecological management objective a very fragmented landscape was generated.

Key words: ecological objectives, habitat suitability index, heuristic optimization, multi-objective forest planning.

Resumen

Examinando variables de paisaje alternativas para una planificación forestal ecológica: caso de estudio para el urogallo en Cataluña

El presente estudio examinó el funcionamiento de cuatro variables de paisaje diferentes; (1) *proporción de hábitat (%H)*, (2) *autocorrelación espacial* (3) *proporción de límites separando parcelas clasificadas como hábitat (H-H)*, (4) *proporción de límites separando parcelas clasificadas como hábitat y no hábitat (H-Non-H)* como objetivos para una planificación forestal ecológica a escala de paisaje en Cataluña. Tales variables de paisaje fueron analizadas en un caso de estudio cuyo propósito era mejorar el hábitat del urogallo en dos montes simulados de 14.400 ha compuestos mayoritariamente por rodales de *Pinus uncinata*, *Pinus sylvestris* y *Pinus nigra*. La aptitud de los rodales como hábitat fue estimada mediante un índice de adecuación de hábitat (HSI) a nivel de rodal. A continuación cuatro problemas de planificación fueron formulados para analizar el funcionamiento de las cuatro variables de paisaje como uno de los objetivos en el problema de planificación forestal. Para ello se formularon cuatro funciones objetivo en forma de función de utilidad aditiva, la cual fue resuelta mediante técnicas de optimización heurística. Con anterioridad, cinco técnicas de optimización heurística: *ascensión aleatoria (RA)*, *Hero*, *templado simulado (SA)*, *búsqueda tabú (TS)* y *algoritmos genéticos (GA)*, fueron comparadas en dos problemas distintos, (1) que incluía %H y

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Received: 22-09-03; Accepted: 24-09-04.

(2) que tenía *H-H* como uno de los objetivos en la función objetivo. Basándonos en tales comparaciones, GA fue seleccionada como técnica más adecuada para problemas de consideración espacial [tipo (2)] y SA para problemas no espaciales [tipo (1)]. La distribución espacial de los rodales considerados hábitat fue similar cuando %*H*, *autocorrelación espacial* y *H-H* fueron incluidos como objetivo ecológico en el problema de planificación. Sin embargo, *H-H* y autocorrelación espacial generaron un paisaje con teselas de hábitat más agrupadas y de mayor tamaño. La mayor proporción de *H-H* se consiguió cuando *H-H* se incluyó como objetivo ecológico. Además, el uso de *H-H* como objetivo fomentó la formación de áreas núcleo de hábitat y la conexión de teselas, reduciendo simultáneamente la cantidad de bordes. Por otro lado, el uso de autocorrelación espacial como objetivo generó una menor superficie de hábitat y de *H-H* que cuando se utilizó %*H* y *H-H* como uno de los objetivos. Aún así el uso de autocorrelación espacial elevó la proporción de teselas de hábitat de gran tamaño. En contraposición, cuando *H-Non-H* se incluyó como objetivo en el problema de planificación, se obtuvo un paisaje fragmentado con respecto al hábitat del urogallo. Por otro lado, las limitaciones de %*H* como objetivo ecológico se acentuaron cuando se utilizó el segundo paisaje forestal que a diferencia del primero no se caracterizaba por una correlación de factores relacionados con la calidad de sitio, que afectaban la composición de especies así como las tasas de crecimiento de los rodales.

Palabras clave: objetivos ecológicos, índice de adecuación de hábitat (HSI), optimización heurística, planificación forestal multi-objetivo.

Introduction

Forest planning has become more clearly multi-objective than earlier, and objectives representing forest uses other than timber production have become more common (Palahí, 2002; Pukkala, 2002a). In several countries, multiple-use planning replaced timber management planning already some decades ago (Pukkala, 2002a). Multiple-use planning considers activities like recreation and hunting together with timber production. Recently, ecological planning has gained importance. The task of ecological planning is to find such a management for the forest that populations of plant and animal species remain viable, i.e. the biodiversity of the forest is maintained (Pukkala, 2002a). Landscape ecological theories and studies provide information on the relations existing between the structure of a landscape and the ecological processes involved in the viability of different species and species groups (Forman and Gordon, 1986; Wiens *et al.*, 1993; Andrén, 1994; Harrison and Fahrig, 1995; Forman, 1995; Angelstam, 1997; Angelstam and Petterson, 1997; Palomares *et al.*, 2000; Kurttila, 2001).

The fragmentation of the habitats of key species is often thought to decrease species' abilities to sustain viable populations (Rodríguez and Delibes, 1992; Andrén, 1994; Helle *et al.*, 1994; Mönkkönen *et al.*, 1997; Jansson and Angelstam, 1999; Palomares *et al.*, 2000; Öhman, 2001). In Spain, Rodríguez and Delibes (1992) found that habitat fragmentation was one of the main factors for the decline of Iberian lynx. Other species with large territorial requirements, like the capercaillie, which is often referred to as an indicator species of

healthy old forest communities in montane ecosystems (Klaus *et al.*, 1989; Menoni, 1991; Storch 1997), are also susceptible to forest fragmentation (Rolstad and Wegge, 1987, 1989; Storch 1995). Therefore, landscape scale aspects of capercaillie habitats need to be considered (e.g., Menoni, 1991; Storch, 1997).

Fragmentation generally refers to the loss of a certain habitat, a reduction in the size of habitat patches and a weakening of the connections between them (Andrén, 1994). Forest planning needs to be capable of dealing with these factors, since many changes that come about in commercially-managed forests are caused by forestry operations. Landscape metrics, which are variables measuring the sizes, shapes, relative arrangement and connectivity of habitat patches as well as their total area, are a way to measure the ecological quality of a given forest (McGarical and Marks, 1995). Kurttila *et al.* (2002), for instance, evaluated the performance of some landscape metrics types in the context of producing forest plans suitable for flying squirrel and moose.

A justified ecological objective is often spatial in nature, and it depends on the locations of different types of forest. A number of landscape metrics can be formulated depending on the ecological process or the organism to be evaluated. However, before calculating any landscape metric, the stands should be classified into different habitat types or, if only one species is concerned, as habitats and non-habitats (Pukkala, 2002b). It is also possible to develop a continuous stand-level habitat suitability index (HSI) (Kurttila *et al.*, 2002) which indicates the suitability of a single stand as habitat for a certain species.

In early 1980s, operation research techniques such as linear programming (LP) had increasingly replaced classical regulation methods in forest planning (e.g., Johnson and Tedder, 1983). The ability to analyse alternative activities was enhanced through the use of mathematical programming and simulation techniques (Borges *et al.*, 2002). Yet, mathematical programming could not effectively address large-scale multi-objective problems that encompassed transportation considerations or spatial considerations due to ecological objectives (Borges *et al.*, 2002; Palahí, 2002; Pukkala, 2002a). The computational complexity of these problems has resulted in increased adoption of heuristic optimization techniques in forest planning calculations. These techniques are generally more flexible and capable of addressing more complicated objective functions and constraints than exact algorithms (Reeves, 1993; Borges *et al.*, 2002). However, their disadvantage is that often the quality of the found solution remains unknown. Simulated annealing (SA) (e.g. Dahlin and Sallnäs, 1993; Lockwood and Moore, 1993; Öhman and Eriksson, 1998; Öhman, 2000), tabu search (TS) (e.g. Bettinger *et al.*, 1997; Boston and Bettinger, 1999) and genetic algorithms (GA) (e.g., Bettinger *et al.*, 2002) have been the most often applied basic techniques. In Finland a simple heuristics call Hero has been used for a decade for both non-spatial (Pukkala and Kangas, 1993) and spatial (Pukkala *et al.*, 1995) forest planning problems.

The aim of the study was to test the performance of different landscape metrics in a planning situation where the maintenance of capercaillie (*Tetrao urogallus*) habitats was a management objective together with timber harvesting. Before this analysis, various heuristics were compared to find the best optimisation method for different types of problem formulation. All calculations were done using a Spanish forest planning system for Catalonia, MONTE (Palahí, 2002; Pukkala, 2003).

Material and Methods

The case forest

The study was conducted in a simulated artificial forest landscape, representing montane conditions in Catalonia (north-east Spain). The forest contained 900 forest stands of 16 ha each distributed as a 30 × 30 stand grid. The total area of the landscape was 14,400 ha. The simulated artificial landscape was developed

by using real forest inventory data from the second Spanish National Forest Inventory (ICONA, 1993). All National Forest Inventory plots in Catalonia which contained *Pinus uncinata*, *Pinus sylvestris*, *Pinus nigra* or mixtures of them and located between 1,000 and 1,900 meters above sea level were used to compose the artificial landscape. The forest data of the inventory plots were assigned to the grid cells according to altitude so that the resulting forest was a big slope ranging from 1,000 to 1,900 m in elevation. The artificial landscape tried to resemble typical forests in the Pyrenees where the habitat of capercaillie in Catalonia is found. The adjacency information corresponding to this setting was generated for spatial optimization.

The stands were rather dense, the mean growing stock volume being about 150 m³/ha. Common stand volumes decreased from about 300 m³/ha to 50 m³/ha when one moved from 1,000 m a.s.l. to 1,900 m. *Pinus uncinata* was the dominant tree species at 1,900 m but it was replaced by mixtures of *P. uncinata* and *P. sylvestris* and pure *P. sylvestris* at mid-elevations. The presence of *P. nigra* increased when one approached 1000 m, but the area and total volume of *P. nigra* were much smaller than those of *P. uncinata* and *P. sylvestris*. The stand structures were closer to even-aged than uneven-aged structure, but very few stands were strictly even-aged.

In order to test the sensitivity of the landscape metrics to the initial composition and configuration of the forest landscape, a second artificial forest containing the same number of stands (900 stands distributed as a 30 × 30 stand grid) but in which the same forest data of the inventory plots was assigned randomly to each stand was developed.

Simulation of management alternatives

Alternative treatment schedules were simulated for the stands for a 60-year planning period. This period was divided into three 20-year sub-periods. In these simulations, the stand was thinned once the stand basal area reached the «thinning limit». The stand was regenerated with the shelter tree method (Palahí and Pukkala, 2003) when stand age exceeded the rotation age.

The individual tree-level models for *P. sylvestris*, *P. nigra* and some «accompanying species» developed by Trasobares *et al.* (2004) were used to simulate forest stand development over the 60-year planning period.

Unpublished but structurally similar models developed by Trasobares were also used for *P. uncinata*.

The models developed by Palahí (2002) were used to formulate thinning and rotation instructions (thinning limit and rotation age) for different sites of Scots pine stands. These models were based on a stand-level optimisation study by Palahí and Pukkala (2003), which found optimal management regimes for maximising profitability with 2% discounting rate for different sites in Spain. To produce several alternative regimes for each compartment, the optimal rotation length based on the compartment's site index, was multiplied by 0.7, 1.0 and 1.3. With each rotation instruction, the basal area which activated the thinning (thinning limit) was multiplied by 0.7, 1.0 and 1.3. This produced 9 different management instructions for the stand. The simulation of stand development and treatments during a 60-year period was repeated with every instruction. The purpose of the simulation was to predict the stand development, and to compute removals under different treatment regimes.

Habitat Suitability Index for Capercaillie (*Tetrao urogallus*)

Habitat suitability index (HSI) models are among the most widely used wildlife management tools in North America (Verner *et al.*, 1986; Van Horne and Wiens, 1991). In Europe, habitat models are receiving increasing attention (Storch, 1996; Kuhn, 1998; Storch, 2002) as the need for practical evaluation methods for land management and conservation practice has become recognized (Link *et al.*, 1996; Storch, 2002). Continuous stand-level HSIs are used to evaluate the suitability of a single stand as habitat for a certain species (Pukkala, 2002b). Typically, a HSI model summarizes the conceptual understanding of the habitat relationships of the target species, based on literature reviews, expert opinions, or research studies (Storch, 2002). A set of variables is identified and combined into a series of simple equations. The resulting HSI score ranges between 0 for unsuitable and 1 for optimal habitat suitability. The procedures of HSI model development have been summarized by Schamberger and O'Neil (1986), Van Horne and Wiens (1991) and Morrison *et al.* (1992).

Capercaillie has seasonally distinct habitat needs. In winter, they feed on conifer needles and spent most of their time on the trees, whereas in summer they

prefer habitats with abundant ericaceous shrubs, particularly bilberry, *Vaccinium myrtillus*, for food and cover (Storch, 2002). However, information on ground vegetation is seldom included in forest inventory, so its development is not easily predicted. Therefore, in this study, the HSI used was restricted to capercaillie winter-feeding habitats. The model for capercaillie winter-feeding HSI in Catalonia was adopted from a previous study by Pascual (2003). The variables used to compute the HSI were: (1) proportion of *Pinus sylvestris*, *Pinus uncinata* and *Abies alba* of stand volume, (2) stand density (number of trees per hectare), and (3) number of trees greater than 30 cm in diameter at breast height (dbh). For more details see Pascual (2003). If the proportion of *Pinus sylvestris*, *Pinus uncinata* and *Abies alba* volume in a stand was 100%, the stand density was within 100 and 700 stems ha⁻¹, and the number of stems per hectare with dbh greater than 30 cm is equal to or greater than 5, then the HSI equals 1 and the stand is considered a good winter-breeding and foraging habitat. The information generated in the simulation of management instructions was used to compute the capercaillie winter feeding HSI for every stand at the end of each sub-period of the 60-year planning horizon.

In this study, a HSI with a value of 0.5 was considered the threshold for defining a stand as a suitable habitat for capercaillie. A clear threshold was required for some of the landscape metrics tested in the study. In most cases the HSI was either 0 or 1, intermediate values representing only about 15 % of stand states.

Heuristic optimisation techniques

In the first stage, five heuristic techniques were tested with two different forest management planning problems. The first problem used a non-spatial landscape metric and the second problem a spatial metric as a management objective. The purpose was to find the best heuristic technique for non-spatial and spatial planning problems. In the second stage, the performance and outcome of four landscape metrics were analysed using those heuristics that ranked best in the first stage.

The heuristic techniques tested in the first stage were random ascent, Hero, simulated annealing, tabu search and genetic algorithms. They were described by Palahí and Pukkala (2004) and more in detail by Reeves (1993).

Landscape metrics

Four landscape metrics were analysed as means to affect the pattern and amount of capercaillie habitats in numerical optimisation: (1) proportion of suitable habitat; (2) spatial autocorrelation; (3) the proportion of habitat-habitat boundary and (4) the proportion of habitat-non-habitat boundary.

Proportion of HSI

In the case of this landscape metric, information related to landscape configuration (spatial character of patches within the landscape) is not used. The proportion of HSI is a quantitative measure of landscape composition referring to the relative amount of suitable forest stands ($HSI \geq 0.5$) for the habitat of capercaillie within the landscape. The proportion of HSI (%H) is calculated as follows:

$$\%H = 100 \times \frac{\sum_{i=1}^n (HS_i \times a_i)}{\sum_{i=1}^n a_i} \quad (1)$$

where %H is the proportion of stands suitable as habitat for capercaillie, HS_i is a variable which either 0 ($HS_i < 0.5$) or 1 ($HS_i \geq 0.5$) defining stand i as non-habitat or habitat, respectively, a_i is the area of a stand i and n is the total number of stands in the forest landscape.

Spatial autocorrelation

Spatial autocorrelation measures the relative locations of different stands, indicating the general similarity or dissimilarity of neighbouring stands at the forest level (Kurttila *et al.*, 2002). Moran's I is one measure for spatial autocorrelation, which is calculated by the following formula (Reed and Burkhart, 1985; Chou *et al.*, 1990):

$$I = \frac{n \sum_{i=1}^n \sum_{j=1}^n a_i a_j W_{ij} (x_i - \bar{x})(x_j - \bar{x})}{S_0 \sum_{i=1}^n (x_i - \bar{x})^2} \quad (2)$$

where n is the number of stands, x the value of variable of interest (HSI in this study), a the stand surface area,

and $S_0 = \sum_{i=1}^n \sum_{j=1}^n a_i a_j W_{ij}$ is the sum of the area-weighted

spatial weights. The spatial relationship was defined in the simplest way, by contiguity, i.e., W_{ij} is 1 if stands i and j are adjacent, otherwise 0. The area weights of Equation 1 might be replaced by other weighting functions (Chou *et al.*, 1990).

The values of Moran's I may vary between -1 and $+1$. A low value indicates that neighbouring stands within a landscape have different values of the stand variable of interest while a high autocorrelation value implies a smooth landscape with gradual changes between adjacent stands.

Habitat-habitat stand boundary

This type of landscape metric refers to the physical distribution or spatial character of patches within the landscape (landscape configuration). Stand boundaries are bisected into two groups, separating two similar or dissimilar stands, according to a threshold value of HSI (Kurttila *et al.*, 2002). Then, the proportion of habitat-habitat stand boundary of the total boundary length is calculated. The idea for using the proportion of habitat-habitat stand boundary is that stand development and treatments during the planning period affect the classification of a stand, and when such a metric is maximised, suitable stands tend to be clustered into groups or corridors increasing connectivity and decreasing fragmentation.

Habitat-non-habitat stand boundary

When habitat-non-habitat stand boundary is maximised the edge zones of habitat patches will increase. Although habitat edges may not be beneficial for capercaillie, this landscape metric was included in the analyses to learn about its behaviour in numerical optimisation. Within a landscape a high proportion of habitat-non-habitat boundary indicates a fragmented landscape with respect to a certain habitat.

Planning problem formulation

Four different planning problems were formulated to test the four landscape metrics as one of the

management objectives. The objective functions of the problems were written in the form of an additive utility model (see, e.g., Pukkala, 2002a, for more details on multi-attribute utility theory):

$$U = 0.6u_h(H) + 0.4u_l(L_{l2063}) \quad (3)$$

where U is the total utility, u_h is the partial utility for the total volume harvested during the 60-year planning period, u_l is the partial utility for the ecological objective variable represented by landscape metric l at the end of the planning period. H and L_{l2063} are the total harvested volume and the value of the landscape metric l at the end of the planning period, respectively. The sub-utility functions transform the absolute values of the variables measured in their own units to a relative sub-utility value. These functions were determined through the smallest and largest possible value of the objective variable, and the respective priorities.

The relative sub-utility values were weighted by the relative importance of the objective variable and summed. The weight of the production objective was 0.6 whereas the weight for the ecological objective represented by a given landscape metric was 0.4. The sensitivity of the solution to the objective weights was analysed with each of the four landscape metrics by varying the weights of objectives and resolving the problem after every change.

Results

Heuristics

To compare the results of the five heuristic optimization techniques, we solved two different planning problems with each technique. One problem was spatial with habitat-habitat boundary as a management objective whereas the other problem was non-spatial using the proportion of HSI as a management objective. To evaluate the quality of the resulting solutions the maximum and average objective function values of 10 repeated optimisations as well as the average time consumption of the techniques were analysed.

In the spatial forest planning problem GA always found the best solution while the other heuristics performed equally well (Fig. 1). GA, although finding a superior solution, was the slowest technique, while Hero was the fastest method. In the non-spatial problem, four of the five heuristic optimization techniques

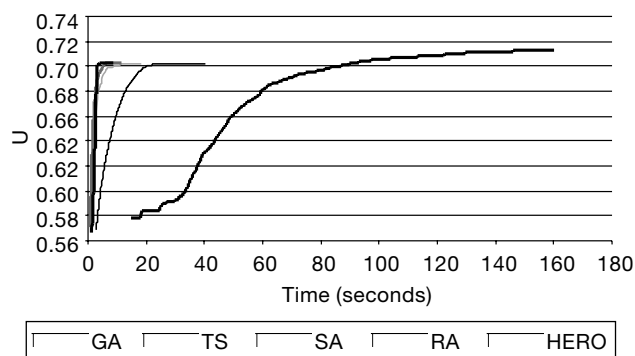


Figure 1. An example of the development of the objective function value in a spatial forest landscape planning problem (when H-H was a management objective) in different heuristic optimization techniques.

performed very similarly. GA was the only technique that found a clearly inferior solution (Fig. 2).

Based on these comparisons, it was concluded that GA should be used in our study for spatial planning problems, while SA was good in non-spatial problems. The choice of SA was partly based on results from other studies. For instance Bettinger *et al.* (2002) and Pukkala and Kurttila (2003), found that SA is a suitable heuristic for non-spatial planning problems. However, due to the time consumption of GA in very complex spatial problems (many hours), the planning problem using spatial autocorrelation as a management objective was also solved by the SA technique.

Performance of landscape metrics

The effects of using the four different landscape metrics as an ecological management objective were

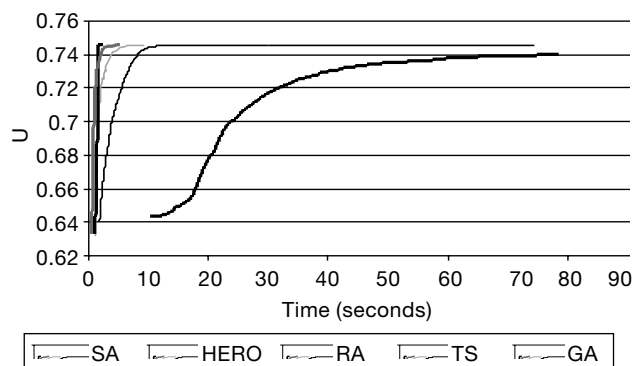


Figure 2. An example of the development of the objective function value in a non-spatial forest landscape planning problem (when %H was a management objective) in different heuristic optimization techniques.

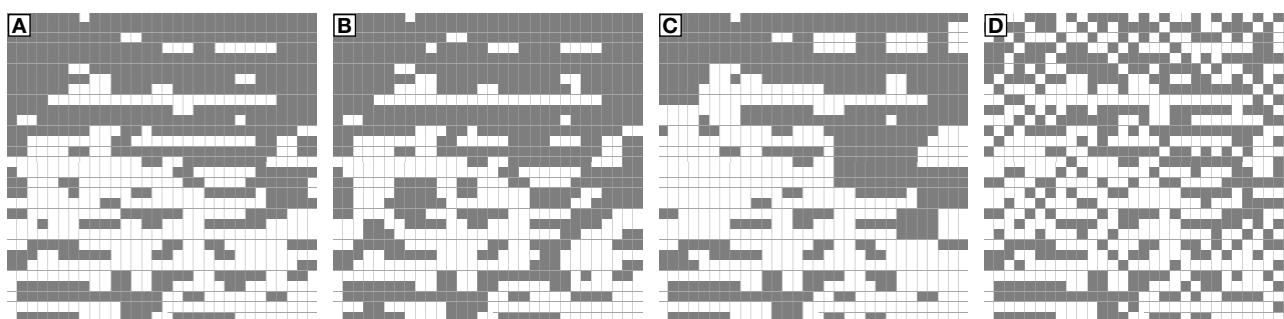


Figure 3. Effect of type of landscape metric used as a management objective on the spatial distribution of habitat patches at the end of the 60-year planning period. The weight of ecological objective is 0.4: a) proportion of suitable habitat (%H). b) habitat-habitat boundary. c) Spatial autocorrelation. d) Habitat-non-habitat. Shadowed cells corresponds to stand suitable as habitat for capercaillie.

evaluated analysing the spatial pattern of capercaillie habitats at the end of the 60-year planning period (Fig. 3).

Figure 3 shows the effect of landscape metric used on the spatial distribution of habitat patches at the end of the planning period. The use of the proportion of habitat suitable for capercaillie (%H) resulted in surprisingly clustered landscape although the metric is non-spatial (top left in Fig. 3). The spatial pattern of habitat patches is comparable to the landscape structure that resulted from the use of habitat-habitat boundary (H-H) or spatial autocorrelation as a management objective (top right and bottom left in Fig. 3). However, the proportion of habitat-habitat boundary and spatial autocorrelation yielded a slightly more clustered landscape with larger habitat patches.

When the proportion of habitat suitable for capercaillie at the end of the 60-year planning period was used as a management objective the proportion of suitable habitat was 56.22% of the total forest area, the value of spatial autocorrelation was 0.0312 and the proportion of habitat-habitat boundary of the total boundary length was 42.58% (see Table 1). However, the largest proportions of habitat and habitat-habitat

boundary were created when using the proportion of habitat-habitat boundary as the ecological management objective (see Table 1).

The use of spatial autocorrelation as a management objective resulted in smaller habitat area and habitat-habitat boundary than the use of %H and H-H objectives (see Table 1). However, the proportion of large habitat patches was rather high (see Fig. 3). A special feature of spatial autocorrelation is that unsuitable stands also tend to cluster generating a less fragmented landscape. In fact, the lowest proportion of habitat-non habitat boundary (22.70%) was achieved by using spatial autocorrelation (Table 1).

In any case, it seems clear from Fig. 3 that an optimal landscape configuration, in this case study, would allocate stands at the lowest elevations (dominated by productive stands of *P. sylvestris* and *P. nigra*) for timber production forest and the stands at higher elevations (dominated by *P. uncinata*) to create large habitat patches for capercaillie.

The bottom right of Fig. 3 shows the spatial structure of the forest at the end of the planning period when habitat-non habitat was used as the ecological management objective. It is clear that a very different spatial structure of the same forest landscape could be

Table 1. Proportion of suitable habitat for capercaillie (% H), spatial autocorrelation, proportion of habitat-habitat boundary (% H-H), and proportion of habitat-non-habitat boundary (%H-NonH) when using the variable in the first column as an objective variable in a two-objective planning problem

Objective variable	% H	Spatial autocorrelation	% H-H	% H-NonH
% H	56.22	0.0312	42.58	26.43
Spatial autocorrelation	51.00	0.0362	39.19	22.70
% H-H	61.88	0.0254	48.27	26.66
% H-NonH	46.00	-0.0027	20.17	51.55

achieved by using a different landscape metric as a management objective.

The sensitivity of the four landscape metrics to the weight of the metric used as the management objective was analysed (Fig. 4). Spatial autocorrelation (Moran's *I*) was rather sensitive to the choice of metric used as objective variable, while the proportions of suitable habitat and habitat-habitat boundary were less sensitive, except when maximising habitat-non-habitat boundary. Spatial autocorrelation achieved almost maximal levels already with small to medium weights when the proportion of habitat or habitat-habitat boundary was used as an objective. However, when greater weights were given to these metrics spatial autocorrelation started to decrease. On the other hand, the proportion of habitat-non-habitat boundary decreased already with small weights when spatial autocorrelation was maximised, while when habitat-habitat boundary was maximised this needed greater weights than spatial autocorrelation to reduced habitat-non-habitat boundary at the same levels. When spatial autocorrelation was maximised with increasing weights, also the proportion of suitable habitat and

habitat-habitat boundary increased, while the proportion of habitat-non-habitat boundary decreased. However, the same is not true when %H and H-H were maximised.

Figure 5 shows the effects of the same landscape metrics in this random landscape that has no trends in stand characteristics. In this forest, spatial autocorrelation yields the most clustered landscape by the end of the 60-year planning period (bottom left in Fig. 5). The use of habitat-habitat boundary results in smaller habitat patches, but the patches are usually connected to each other. On the other hand, the limitations of a non-spatial metric, like the proportion of suitable habitat, are quite evident in this case (top left of Fig. 5).

Discussion

In the process of managing the maintenance of viable population's species, the problem can be approached from the perspective of a single species, of the ecological processes involved, or at the level of landscape (Knight, 1998). In the first approach the emphasis is on the habitat needs of certain species,

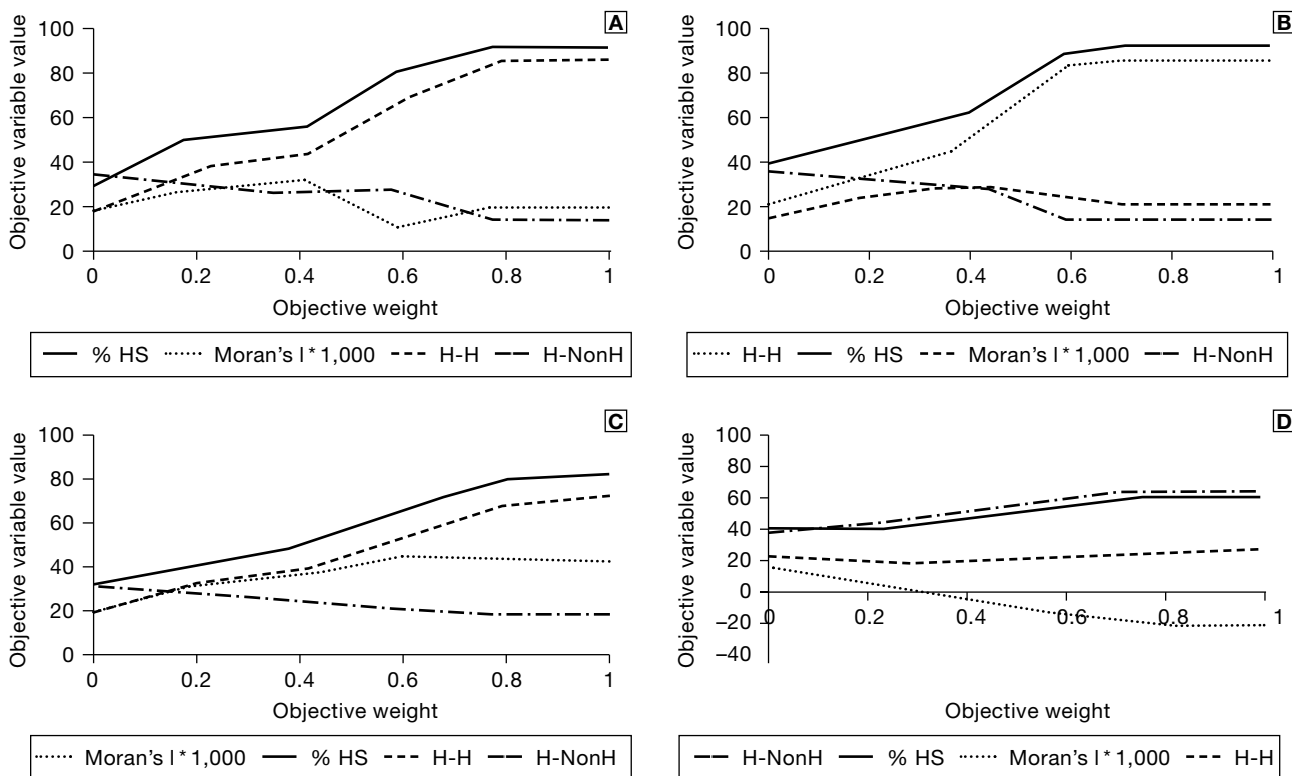


Figure 4. Sensitivity of the four different landscape metrics to changes of the weights of the ecological objective maximised in the planning problem. The landscape metrics were: a) proportion of suitable habitat (%H). b) proportion of habitat-habitat boundary (H-H). c) Spatial autocorrelation, and d) proportion of habitat-non-habitat boundary (H-NonH).

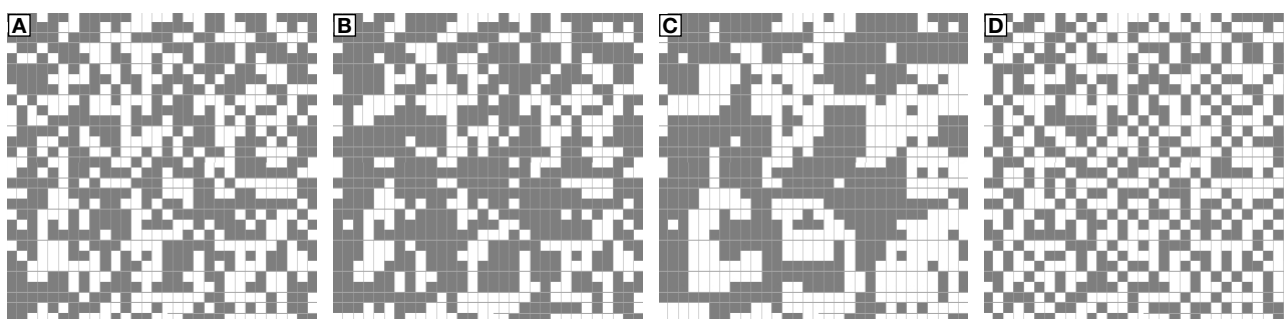


Figure 5. Effect of type of ecological objective on the spatial distribution of habitat patches at the end of the 60-year planning period in the randomly created forest landscape. The weight of ecological objective is 0.4: a) proportion of suitable habitat (%H). b) habitat-habitat boundary. c) Spatial autocorrelation. d) Habitat-non-habitat. Shaded cells corresponds to stand suitable as habitat for capercaillie.

while the focus of the landscape-level approach is on collectively influencing groups of species by influencing landscape patterns. On the other hand, the ecological processes approach concentrates on ensuring undisturbed functioning of ecological processes (Kurttila, 2001). If the existence of some critical species is at stake, it may be justified to include species-specific objectives in a planning problem. Recent studies by Mazerolle and Villard (1999) and Storch (2002) concluded that both small scale and landscape-scale characteristics of the habitat should be included in models explaining and predicting the distribution and abundance of vertebrate species. Other studies, e.g., by Wiens *et al.* (1993), Andr n (1994) and Harrison and Fahrig (1995), emphasised the importance of the configuration of habitats, i.e. their sizes, shapes and relative arrangement, and their connectivity to maintain the viability and abundance of various species.

In this study, before studying the performance of different landscape metrics, the stands of the forest landscape case study were classified as habitats and non-habitats for capercaillie. To classify the stands the HSI model for capercaillie developed by Pascual (2003) for Catalonia was used. The validity of the used HSI model was not the most essential point in this study. The model was based on a combination of expert opinion and previous research studies in different countries (Pascual, 2003). Subjective reasoning was applied when defining the sub-priority functions for certain habitat attributes (Pascual, 2003). We are aware of the limitations of the model, which included only variables affecting capercaillie winter-breeding habitats and are available in forest planning calculations. Currently, there are several ongoing studies in Spain on capercaillie habitat preferences which make it possible to update the model in the near future using

more accurate information based on empirical data collected in Spain.

The study was conducted in two artificial forest landscapes, ranging from 1000 to 1900 m in elevation, where forest stand inventory data were assigned according to the altitude in the first case and randomly in the second case. Therefore, the performance of and selection of different landscape metrics should be seen within the initial characteristics of the case forest landscapes.

The five heuristic optimization techniques tested in the study were used with two different forest planning problems; one containing a non-spatial landscape metric and the other a spatial metric as management objective. The main result was that differences between the objective function values were small in both problems. However, in the non-spatial planning problem GA performed worse than any other technique, while in the spatial problem GA was clearly the best technique in terms of objective function value. This latest result agrees with the study of Pukkala and Kurttila (2003) who found that GA was especially suitable for solving complex planning problems with spatial objectives. The study of Bettinger *et al.* (2002) compared several of the optimisation techniques tested in this study. Bettinger *et al.* (2002) categorized SA and TS as very good, TS (depending on the situation) and GA as adequate and RA as less than adequate. Our study revealed that different techniques are good for different problems, indicating that ranking is not straightforward. The explanation for GA being the best in spatial problems might be that GA can examine multiple changes in a solution with each iteration.

The ultimate goal of using heuristic techniques is to produce high quality solutions in short amounts of time to problems with non-linearities or combinatorial

relationships. In the future, the need for a standard set of data and criteria for evaluation of these techniques seems appropriate (Bettinger *et al.*, 2002), while the methodological development should concentrate on the specific needs of forest planning problems (Pukkala and Kurttila, 2003).

In this study, the performance of different landscape metrics was illustrated in a case study, which dealt with capercaillie habitats. However, similar landscape metrics are also applicable for other ecological planning problems as well as non-ecological ones (Kurttila, 2001). Each of the landscape metrics tested in this study have both advantages and weaknesses, meaning that their ranking is a difficult task. The reasonably good performance of the three landscape metrics (%H, habitat-habitat boundary and spatial autocorrelation), even of the non-spatial one in the first case study (Fig. 3), may be due to positive and strong autocorrelation of site factors due to the altitudinal gradient, which affects the species composition and growth rate of stands. However, Figure 5 shows that the same metrics performed differently in a completely different forest landscape. In both case studies (bottom left in Figs. 3 and 5) spatial autocorrelation was successful in aggregating and dispersing stands with desired habitat characteristics and created large clusters. This result agrees with the study of Kurttila *et al.* (2002), which tested alternative spatial objective to improve the habitat for flying squirrel and moose. Because spatial autocorrelation does not require the bisecting of stands into habitats and non-habitats, but uses the whole range of HSI, it is likely that the HSI of the final landscape changes gradually. This means that so-called dispersal habitats (low but non-zero HSI) surround foraging and breeding habitats (high HSI) in many places. Therefore, considering that usually a continuum of habitats in time and space is favourable for the long-term maintenance of viable populations of endangered vertebrate animal species, spatial autocorrelation can be an appropriate objective to generate such a continuum.

However, in our study spatial autocorrelation resulted in a lower total area of habitat (area with HSI ≥ 0.5) than when %H or habitat-habitat boundary was used. This is because continuous areas of non-habitat contribute to the Moran's *I* as much as continuous habitat areas. Therefore, in many cases, spatial autocorrelation should be used together with another landscape metric like the total habitat area (Pukkala, 2002b). Another disadvantage of spatial autocorrelation is that the coefficient must be recomputed after every change in

the solution, using all stands, because a change in a stand may affect the mean value of the variable to which other stands are compared. As result the optimisation problem can become too tedious and time consuming, especially when interactive forest planning is pursued. In our study, for instance, SA replaced GA (the slowest optimization algorithm) when solving the problem that included spatial autocorrelation as the management objective.

The proportion of habitat-habitat boundary was very suitable for simultaneously increasing the amount of habitats and improving their spatial pattern (top right in Fig. 3 and 5). Since such a metric considered stand boundaries between neighbours, it promoted the formation of core areas and reduced the amount of edges. Furthermore, habitat-habitat boundary was very successful in connecting patches (top right in Fig. 3 and 5). However, the quality of the other neighbouring stands in the vicinity is not considered by this metric, resulting in smaller clusters than when spatial autocorrelation was used.

The limitations of using a non-spatial landscape metric like the proportion of suitable habitat are clear from Fig. 5. This metric could increase the amount of habitats in both case forests (top left in Fig. 3 and 5) but was not as successful in improving their spatial pattern in a landscape with lacking trends in site productivity. However, it creates much edge zone, which might be good for some species (see Kurttila *et al.*, 2002).

The landscape metrics used were not directly linked to any landscape-level habitat model for capercaillie and the aim was just to improve the spatial configuration of habitats. If known, for instance, a minimum size requirement of habitat patches could have been added to the calculations.

Each metric may have advantages and disadvantages depending on the needs of a specific planning situation. Therefore, it is important to know both the patterning of the landscape good for the different species as well as the way landscape metrics behave as variables in planning optimization problems.

Conclusions

In this study, features from different approaches, landscape-level metrics together with stand-level species-specific models, proved to be a good alternative to solve practical ecological forest landscape planning

problems. In this context, it is important to fully understand the properties of different landscape metrics as well as their performance in different situations before they are used. As the emphasis in landscape ecological planning is on the maintenance of large, dynamic ecosystems, a new kind of approach to the planning of forests is needed. Pukkala *et al.* (1997) termed such an approach as regional planning, in which the planning area could include several forest holdings. Regional planning emphasises cooperation between forest owners, ecological experts and other planning staff. At the regional planning level, the use of landscape metrics, as the ones presented in this study, is more appropriate than at the forest holding level, where the possibilities to affect the structure of the landscape are quite limited. This kind of situation calls for problem formulations in which spatial landscape metrics to enhance certain habitats are considered across a region while timber production and other objectives are dealt with at the forest holding level. This type of planning model is likely to improve in comparison to forest-holding level planning the spatial pattern of habitats.

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