How do changes in land use pattern affect species diversity? – An approach for optimizing landscape configuration

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Abstract

Heterogeneity of agricultural landscapes is supposed to be of significant importance for species diversity in agroecosystems. Thus it is necessary to account for structural aspects of landscapes in land management decision processes. Spatial optimization models of land use can serve as tools for decision support. These models can aim at various landscape functions like nutrient leaching and economical aspects, water quality or habitat suitability. However neighbourhood effects stay unconsidered in most of these approaches. In this paper we present an optimization model concept that aims at maximizing habitat suitability of selected species by identifying optimum spatial configurations of agricultural land use patterns. Bird species with diverging habitat requirements were chosen as target species. Habitat suitability models for these species are used to set up the performance criterion. Landscape structure is quantified by landscape metrics estimated within the species home range. Statistical significance of these metrics for species presence was proven by a logistic regression model. The landscape is represented by a grid based data set. Based on a genetic algorithm the optimization task is to identify an optimum configuration of model units. These model units are defined by contiguous cells of identical land use. Within this concept we can study how optimum but possibly artificial landscapes vary in structure depending on the selected species for which habitat suitability is maximized. The results reflect the habitat requirements of the different species and show where habitat requirements diverge between the species.

Keywords: Genetic algorithm; landscape structure; habitat suitability; multi-criteria optimization

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1. Introduction

Landscape ecology deals with the relationships between landscape structure and function and its changes over time. Landscape structures have important influences on various ecosystem functions (e.g. species diversity, biodiversity, nutrient cycles and water balance). The effects of composition and configuration of different landscape elements on species richness in agroecosystems were examined by several authors (Robertsson et al. 1990, Dunning et al. 1992, Marino & Landis 1996, Jonsen & Fahrig 1997, Weibull et al. 2000, Kerr 2001). Weibull et al. 2003 showed that species richness generally increases with landscape heterogeneity. As species habitat requirements diverge and some wildlife species need different life requisites, changes may have positive effects on one species and negative effects on other species or landscape functions. For example some species prefer compact habitats and other species depend on boundary structures like forest edges or hedges. Some species use different habitat types for breeding and foraging. Thus land use changes may lead to an increase in suitable habitat for one species, but to habitat loss and fragmentation for another species with diverging habitat requirements. To investigate these effects, spatial optimization techniques can be used. They allow a trade off between different management objectives and can be applied to optimize the spatial layout of management actions across the landscape in which an ecosystem functions. General areas of application are the management of wildlife habitat, recreation areas, water runoff, pest management or timber management (Hof & Bevers 1998), but also the development of hypothesis about ecosystems (Hof et al. 2002). Several different optimization approaches exist that underlie different assumptions and can be applied to different problems. For example linear programming (LP) is one of the first methods used to support management decisions (Thompson et al. 1973). It assumes that interactions between neighbouring stands can be ignored. Other approaches are integer programming (IP) and mixed integer programming (MIP). These approaches can only handle problems of limited size and complexity. Advanced approaches are dynamic programming (DP), non-linear programming (NLP) and Monte Carlo integer programming (MCIP). However, all these approaches are not sufficient for the integration of complex spatial dependencies. Approaches that overcome these restrictions and are able to solve highly complex problems are heuristic techniques like simulated annealing (SA), tabu search (TS), interchange methods, genetic algorithms (GA) and neutral networks (Narendra 1996).

Lots of applications of optimization approaches are spatially explicit, but however, most of the optimization approaches cited in the literature disregard neighbourhood interactions (Nevo & Garcia 1996, Church et al. 2000, Randhir et al. 2000, Seppelt & Voinov 2002). There are only a few approaches that take into account neighbourhood dependencies. For example Bevers and Hof (1999) use MIP to optimize habitat configuration resulting from forest treatment with respect to wildlife edge effects. A similar approach is carried out by Moore et al. (2000) where population viability is optimized over ten decision periods in a very simple landscape using a GA. Likewise Loehle (2000) uses an interchange method to minimize the impact of timber harvest on edge-sensitive bird species while maximizing timber harvest. Venema et al. (2005) apply a genetic algorithm to optimize forest structures with respect to certain landscape metrics.

This paper presents an approach of a genetic algorithm optimization model that aims at maximizing habitat suitability of three selected bird species by identifying optimum spatial configurations of agricultural land use patterns. Bird species with diverging habitat requirements and preferences in habitat structure were chosen as target species. In contrast to the approach of Venema et al. (2005) in our model not global landscape metrics, but global habitat suitabilities serve as the goal function. The evaluation of these habitat suitabilities is based on static variables like soils or climate factors and landscape structures quantified by landscape metrics (McGarigal et al. 2002). These metrics are estimated within the species home ranges. Thus it is possible to investigate the effects changes may have on habitat suitability for different species. This approach is supposed to answer the following questions:

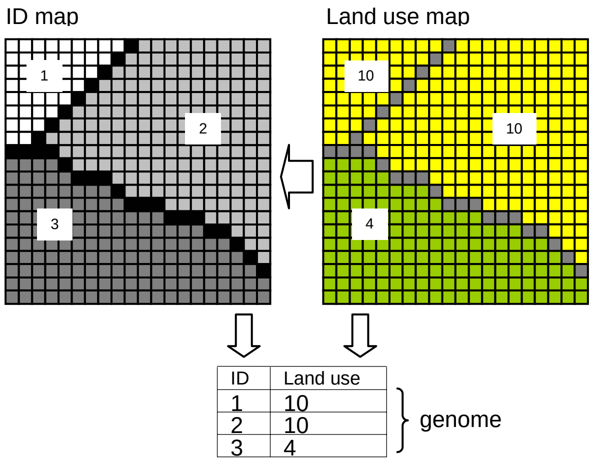
- How do optimum but possibly artificial landscapes vary in composition and configuration depending on the weightings for the selected species for which habitat suitability is maximized?
- How do habitat suitabilities evolve in relation to each other during the optimization process? Where are conflicts between species?

2. Model approach

The model approach that is presented in this paper is designed to allow a trade-off between different ecosystem functions taking into account spatial configurations of landscape elements. It can be used to detect optimum landscape patterns that support certain ecosystem functions like habitat suitabilities for different species with diverging habitat requirements.

With this approach we want to analyse how an improvement with respect to one function affects other functions. Thus the optimization task is to maximize the weighted sum of habitat suitabilities of all selected species for the whole study region by identifying optimum spatial configurations of agricultural land use patterns. As this is quite a complex combinatory problem, we apply a genetic algorithm which is known to be a robust method for gradient-free optimization. We utilized the C++ genetic algorithm library GALib by Wall (1996). To minimize the computational effort and avoid unrealistic land use patterns we defined model units as contiguous cells of identical land use. These model units correspond to patches of agricultural fields, grassland parcels and forest parcels that are assumed to be managed as a whole. Within the model units all grid cell values are changed en bloc. To evaluate the performance criterion, cumulative habitat suitabilities were quantified on raster basis according to the habitat suitability models derived from logistic regression.

The optimization model is based on a discrete grid that represents the study area. Each grid cell has several attributes like a land use type and site conditions (e. g. height). All cells that have an equal land cover and have at least one common edge define a model unit and are identified by a unique identifier in an ID map. The allele set describes the set of land use types that can be modified and it consists of the choice variables “grassland”, “cropland”, “deciduous forest” and “coniferous forest”. As the optimization procedure is supposed to start from the original landscape, the initial population of the GA consists of genomes derived from the original landscape. For this purpose the two-dimensional grid representation of the landscape is transformed into a one-dimensional array of all model units with land use categories of the allele set (Fig. 1). The genome is therefore defined as a one-dimensional array of model units.



ID	Land use
1	10
2	10
3	4

Fig. 1: Transformation of the landscape grid into a one-dimensional array genome

To obtain an initial population of slightly different individuals, some stochasticity was introduced. For this purpose a certain percentage of genes are chosen randomly from the allele set when transforming the initial landscape into the genome. The crossover operator defines the procedure for generating two children from two parent genomes. We applied the one-point crossover operator to our model (Wall 1996). In this case the parent genome strings are cut at some random position to produce two "head" and two "tail" segments. The "tail" segments are swapped to produce two new full length chromosomes. A mutation operator defines the procedure for mutating each genome. It is applied to each child after crossover and randomly alters each gene with a small probability. The value of a single element of the array is flipped to any of the possible allele values. Thus mutation provides a small amount of random search and helps insure that no point in the search space has a zero probability of being examined (Beasley et al. 1993). In our study we apply a "steady-state genetic algorithm". This algorithm uses over-lapping populations, where only a user-specified part of the population is replaced each generation. For parent selection the roulette wheel selection method was used (Goldberg 1989), where the likelihood of selection is proportionate to the fitness score. The size of the section in the roulette wheel is proportional to the value of the fitness function of every individual - the bigger the value is, the larger the section is. After mating the worst individuals are removed from the population to set the population to its original size. Before evaluating the optimization criterion the one-dimensional genome is transformed into the grid landscape representation that is used to assess habitat suitability. The optimization task is to maximize the weighted sum of the cumulative habitat suitability values for the three target species by finding an optimum configuration of land use classes for the parcels that are modifiable.

3. Model application

3.1. Study area

The study was carried out in the administrative district of Leipzig in the Northwest of Saxony, Germany. It covers an area of ~ 441.000 ha. The main land use in this region is agriculture. During GDR-times an industrialisation of agriculture was promoted. Fields were merged to increase the affectivity of cultivation. Fields sizes in our study area go up to 30 ha. The elevation in the study area increases from about 100 m a.s.l. in the North to 250-300 m a.s.l.

in the South East. In the South Eastern area where the relief is stronger, the landscape is more fragmented and agricultural fields are smaller.

Land use data including 20 categories was available for this region with a resolution of 10 m for three time steps (1965, 1984 and 1994). It was derived from satellite imagery in combination with aerial photographs, topographic maps and land use mappings. A digital elevation model with a resolution of 20 m was available from the Federal Land Survey Office Saxony (2001). The digital soil map generated at the Department of Applied Landscape Ecology, UFZ Leipzig-Halle GmbH by intersecting the MMK 25 (Medium-scaled Agricultural Site Mapping) and the WBK (Forest Soil Map) of the Saxonian Federal Bureau of Environment and Geology was used. Based on AG Boden (1994) information on the proportion of soil texture was derived from the mapped soil types. The climate data on the mean annual sunshine duration (between 1961 and 1990) was available from Germanys National Meteorological Service (DWD) with a resolution of 1000 m. Point data on the model species' breeding occurrences between 1963 and 1996 was provided by the local environmental administration (National Bureau of Environment) and digitized at the UFZ Leipzig-Halle GmbH. The bird species middle-spotted woodpecker, woodlark and red-backed shrike were chosen as target species, because they colonise different habitat types. The middle-spotted woodpecker utilizes large compact deciduous forests. The woodlark can be found in coniferous heath forests with dry and sandy soils. The red-backed shrike prefers open and half open areas with boundary structures.

3.2. The habitat suitability models

Statistical habitat suitability models were developed using logistic regression (Fielding & Haworth 1995) based on data of the administrative district of Leipzig. As only presence point data was available for the model species, random sets of pseudo-absence data were generated with sizes equivalent to the specific presence data set. The selection of pseudo-absence data had to be done several times, because different samples could result in different models depending on landscape heterogeneity and species specialisation. For these data points the local values of static habitat variables (e.g. elevation, slope, soils, climate) were stored. To test the effects of structural landscape aspects on habitat suitability, several simple landscape metrics (McGarigal et al. 2002) were calculated for each of these points within a radius of 200 m. This radius corresponds to the species' home ranges (Flade 1994). A set of uncorrelated potential habitat variables was chosen for each species. Based on the presence data and multiple pseudo-absence data sets, 100 logistic regression models were calculated for each species by using the stepwise variable selection procedure (forward and backward). The step function selects a model according to the AIC (Akaike Information Criterion), which corresponds to a penalization term λ of 2 and this is equivalent to an α-level of 0.157 (Reineking & Schroeder 2005). The coefficients of the most frequently occurring model were chosen and averaged to result in the model used for predicting habitat suitabilities in the optimization. The standard deviations can be seen as the standard errors of the averaged estimates. To evaluate the averaged model the area under the curve (AUC) was evaluated based on the datasets of the models the averaged model was derived from. For the red-backed shrike and the woodlark presence data between 1993 and 1995 was correlated to the land use structures from 1994. The data sets included 65 occurrence points for the wood lark and 933 occurrence points for the red-backed shrike. For the middle-spotted woodpecker presence data was very limited and thus presence data from three periods (1963-65, 1979-80, 1993-95) was used and correlated to the land use structure of 1965, 1980 and 1994, respectively. There were 28 occurrence points between 1963 and 1965, 11 between 1979 and 1980 and 28 between 1993 and 1995. The datasets of these three time periods were then combined into one dataset for calculating the multiple habitat suitability models.

For the middle-spotted woodpecker the predictive model was averaged based on 49 models, whereas the wood lark model was derived from 52 models and the model for the red-backed shrike is based on 96 models. The best model fit was achieved for the middle-spotted woodpecker (AUC: 0.97). It includes the habitat variables largest patch index which represents landscape heterogeneity, elevation, mean annual sunshine duration and the proportion of deciduous forest within the species home range. The most important factor is class area of deciduous forest. The model fit of the woodlark model is also very good (AUC: 0.92). It was detected a strong negative impact of the proportion of build-up area within the radius of 200 m and a positive impact of class area of deciduous and coniferous forest. The largest patch index was found to be negatively correlated to species occurrence. The proportion of sand at the specific location has a positive effect on habitat suitability for the woodlark. With an AUC of 0.72 the red-backed shrike model is acceptable. Like both other models it also incorporates a negative effect of the largest patch index. The most important positive factor in this model is the proportion of groves and single trees. This land use class includes mainly small structures with a high proportion of edge. The edge density of cropland within the species home range also has a positive effect on habitat suitability of the red-backed shrike. The variables edge density of coniferous forest, class area of build-up area and the difference between class area and edge density of deciduous forest were found to be negatively correlated to species occurrence. The coefficient of this combined variable shows that edge density of deciduous forest is preferred whereas a high proportion of deciduous forest within the radius is avoided.

3.3. Optimization model

The optimization model was applied to a small landscape subset of 6.8 x 9.2 km from 1994. This subset is located in the Eastern part of the region. The model units were identified based on the original data with a resolution of 10 meters. An ID map was generated, where each patch of the four selected categories was assigned a unique ID. To reduce the computational effort, the optimization was performed based on input grids resampled to 40 m. The GA was set up with the parameters shown in Table 1.

Table 1: parameters of GA application

population size	10
probability of random disturbance in initial population	0.03
probability of cross-over	0.6
probability of mutation	0.01
number of generations	1500
replacement [%]	0.25

To analyse how composition and configuration vary depending on the weightings for the selected species for which habitat suitability is maximized, we carried out a sensitivity analysis with varying species weightings. The optimization was performed for all possible combinations of weightings by increments of 0.1 (66 combinations). For each of these runs the best individual of the final population was evaluated according to a set of landscape metrics and habitat suitability of the model species. For the comparison of the optimization results with the initial landscape the same metrics were used as for the comparisons among the optimization results.

4. Results

Results show that the highest mean habitat suitability values are reached for the middle-spotted woodpecker (mean HSI between 0.43 and 0.84). Almost all optimization runs lead to a higher mean HSI for the middle-spotted woodpecker than for any other species. The optimization was least successful for the red-backed shrike (mean HSI between 0.29 and 0.52). For the wood lark the mean habitat suitability varies between 0.32 and 0.64. As the initial mean habitat suitability index was 0.28 for the middle-spotted woodpecker, 0.27 for the wood lark and 0.36 for the red-backed shrike, the improvement was best for the middle-spotted woodpecker and worst for the red-backed shrike. Habitat suitabilities of all three target species improved during almost all optimization runs except for the optimization runs with respect to habitat suitability for the wood lark. Red-backed shrike habitat suitability decreased compared to the initial state in optimization runs with respect to the wood lark habitat suitability.

Results of the analysis of landscape composition depending on the combination of species weighting show that the middle-spotted woodpecker prefers deciduous forest. The proportion of grassland and cropland is highest in the landscape optimized for the red-backed shrike. The wood lark avoids grass- and cropland and to a certain extent also deciduous forest. When we compare the initial landscape composition with those of the optimization results, we see that the proportion of cropland has decreased during all optimization procedures. Also the proportion of grassland decreased in comparison with the initial landscape except for the optimization with respect to the red-backed shrike. Whereas compared to the initial landscape the proportion of deciduous forest is higher in all optimization results. The proportion of coniferous forest has increased within the optimization for the wood lark and decreased within the optimization for the middle-spotted woodpecker and the red-backed shrike.

The effects of species weightings on landscape configuration on landscape level are as follows. Landscapes optimized with respect to middle-spotted woodpecker show the most homogeneous and least diverse pattern. The red-backed shrike prefers the most diverse and fragmented landscapes and the landscapes optimized for the wood lark are not as homogeneous as those optimized for the middle-spotted woodpecker but not as fragmented and diverse as the landscapes optimized for the red-backed shrike either. Landscape homogeneity is much higher in the initial landscape than in those optimized for the red-backed shrike and the wood lark, but it is lower than in the landscape optimized for the middle-spotted woodpecker. The aggregation of classes is lower in the initial landscape than in those optimized for the middle-spotted woodpecker and the wood lark, but it is slightly higher than in the landscape optimized for the red-backed shrike.

5. Discussion

The results of the sensitivity analysis reflect the habitat requirements of the different species and show where habitat requirements diverge between the species. The fact that the habitat suitability is highest in all runs with a weight for the middle-spotted woodpecker > 0 can be explained by the high sensitivity of the habitat model towards alternations in the GA. The most important factor in the habitat model is the proportion of deciduous forest within the species home range. Thus changes in the GA cause great changes of habitat suitability and habitat suitability can be improved to a higher value. Within the red-backed shrike model the most important factor is the proportion of groves and single trees within the species home range. As this is not a modifiable variable in the GA, the GA causes only slight changes in habitat suitability for the red-backed shrike. The influence of the changeable variables (edge density of coniferous forest, edge density of cropland, and proportion of deciduous forest – edge density of deciduous forest) is low and thus the algorithm converges at a much lower level. The same applies to the wood lark. For this species the most important habitat variable is the proportion of build-up area. The GA influences habitat suitability over the variables “proportion of deciduous forest” and “proportion of coniferous forest”. As the coefficients of these variables have lower values than the coefficients of the changeable variables in the red-backed shrike model, the sensitivity of the wood lark model towards the GA is higher than the sensitivity of the red-backed shrike model, but still lower than the sensitivity of the middle-spotted woodpecker model.

The fact that the optimization with respect to the wood lark led to a decrease of habitat suitability for the red-backed shrike, whereas all other optimization runs improved habitat suitability for all species, indicates that the habitat requirements of the woodlark diverge from those of the red-backed shrike.

6. Conclusions

The approach outlined in this paper proofed to be a suitable tool for analysing the effects of land use changes on different species and detecting conflicts between species. Changes in the GA can be interpreted as management actions. We could show the effects of different management actions on habitat suitability for the model species. An increase of deciduous forest has a positive effect on all target species, at least to a certain extent. An increase of coniferous forest has a positive effect on habitat suitability for the wood lark, whereas for the red-backed shrike juxtaposing patches of cropland, groves and deciduous forest are optimal. The results showed that these management actions are not suitable to improve habitat suitability for all three model species in equal measure. To improve habitat suitability for the red-backed shrike other management actions need to be considered. As this species mainly depends on linear structures like groves, hedges and single trees, linear changes need to be incorporated into the optimization approach.

7. Further work

We plan to use land use suitabilities to promote changes to land use categories that are most suitable for the specific location. Thus the evolving pattern is supposed to be more realistic. Further constraints should be incorporated into the model to guarantee minimum and maximum areas for each land use type. The restrictions could be given through different land use change scenarios developed by the IAP (Institute for Agricultural Policy, Market Research and Economic Sociology, University of Bonn). These scenarios consider political, economic and environmental aspects and give prognosis assuming different policies. An application of the optimization model to areas with different structures of model units is supposed be used to investigate the effects of different structures on optimisation results.

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