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Impacts of Woodland Fragmentation on Species' Occurrences – The Combination of a Habitat Model with Landscape Metrics

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1. Introduction

Habitat fragmentation can be defined as the modification of once natural habitats into smaller, isolated subareas surrounded by other types of habitat (more or less hostile; the matrix; e. g. Valladares et al., 2006). Fragmentation includes both, the separation of habitats and habitat loss, but the most dramatic and consistently negative effects on biodiversity can be attributed to habitat loss (Fahrig, 2003). In our central European man-made landscape more and more habitats become destroyed or fragmented because of the increasing anthropogenic need of available land and despite the growing knowledge about the problem. Roads, residential, and industrial areas separate formerly connected habitats into small remnants and thus create small subpopulations. Accordingly, habitat fragmentation and the associated effects like (1) the biodiversity decline of stenotopic species in smaller habitats (Desender et al., 1999; Magura et al., 2001), (2) the loss of genetic diversity and variability (Debinski & Holt, 2000; Keller & Largiader, 2003), and (3) a higher probability of inbreeding in smaller populations, belong to the main reasons for extinction of species (Groom et al., 2006). Especially stenotopic species with low dispersal power are endangered because the exchange of specimen between different habitat patches is reduced or entirely inhibited (Hanski et al., 1995). Thus, standardised, comprehensible quantification methods of fragmentation are greatly important for the development of management and conservation plans for habitat networks.

Species distribution models have become more and more important tools to analyse species-habitat relations in ecological and conservation research (Guisan & Thuiller, 2005). The principal aim of such habitat models is to predict habitat suitability for the species as a function of the given environmental variables (Basille et al., 2008). Based on biotic and abiotic key factors habitat models allow the quantification of habitat quality for selected species (Kleyer et al., 1999). For this reason they can help to predict the occurrence of rare and often hidden species (Pearce et al., 2001). Furthermore, the model predictions can be used to estimate influences of landscape changes on different species, to find habitats for resettling species and, to identify potential conflicts concerning anthropogenic activities (Klar et al., 2008; Kramer-Schadt et al., 2007).

Given the conservation status of many species, it is becoming increasingly important to understand the relationship between patterns of species' occurrences and the landscape environment. In fact, landscape approaches are relevant for conservation management because landscape planning and management is conducted on wide scales (Franklin, 1993). Landscape condition, which includes properties of landscape pattern as fragmentation, isolation, and patch size, is often not easy to understand, and yet this is very important for deciding how to manage problems like habitat loss, reconstruction and/or habitat (re-) connections (Mortelliti et al., 2010; 2011).

Before the interactions between landscape patterns and ecological processes can be understood the landscape structure must be quantified in meaningful ways (Turner, 1989). The condition and changes of spatial pattern of landscape can be quantified by statistical measurements, so called landscape metrics or indices (Gustafson, 1998; McGarigal & Marks, 1995; O'Neill et al., 1988). In this study we investigate the shape, pattern and the fragmentation status of the German woodlands by means of landscape metrics and analyse the impacts of fragmentation on different FFH species' occurrences.

The results can be used (1) to estimate the level of fragmentation of the studied woodlands, (2) to predict potential occurrences of the species in other woodland areas, and (3) to analyse the suitability of the calculated landscape metrics to predict the occurrence of threatened species. Accordingly, linking landscape metrics with species' occurrences can be an important approach to support the development of management plans in nature conservation.

2. Methods

2.1 Landscape metrics as measure of degree of fragmentation

Jaeger (2003) describes the fragmentation of landscape elements as a process with regard to the change of landscape structure, whereas the degree of fragmentation represents the state of the landscape at a specific time. Landscape metrics can be successfully used to characterise the condition of a landscape at different time points, they are useful tools for the comparison of different landscapes (Turner et al., 2001). Landscape patterns can be differentiated by means of landscape indices from GIS databases, which contain e. g. classifications of remote sensing data like aerial photographs or satellite imagery. An advantage is the efficient analysis of large areas with standardized methodological approaches, which allows generalization at large spatial and temporal scales.

We selected 19 landscape indices that can be used to quantify fragmentation of woodlands through an assessment of the literature (see annex for details).

2.2 Data and preparation

The basis for an adequate use of landscape metrics is the complete mapping of full coverage of the land use and land cover respectively with non-overlapping, integrated, and unambiguous landscape objects. If thematic maps fulfil these prerequisites, geographic information systems (GIS) can be used to analyse the maps with regard to shape, structure, and distribution of landscape elements.

The digital landscape model (DLM) from ATKIS¹-data (year 2008) was the basis for our calculation of landscape metrics. The DLM provides a topographic description of the landscape of the Federal Republic of Germany in a vector format on a scale of 1:25000. Currently, it contains the most detailed spatial data in Germany which provide a comprehensive description of shape, location, and distribution of woodland patches. One decisive factor for the choice of these data is the inclusion of linear elements with potential separating impact on forested areas.

The DLM describes objects in the landscape as a result of definitions of the ATKIS-based feature type catalogue (ATKIS-OK), which allows the classification of more than one single feature type at one spatial point/area. Non-redundant binary maps of woodland and non-woodland were created by aggregating feature classes (see steps in figure 1). At this, the thematic feature types 'forest' and 'grove' were combined to the new class 'woodland'. Polygons, which describe urban, transportation, water, and vegetation areas (except forests and groves) were aggregated to the class 'non-woodland'. 'Woodland' geometries were overlaid by 'non-woodland' and by buffered forest-separating linear elements (e. g. roads, rivers, railways, etc.). The selection of these lines follows the approach described in Jaeger et al. (2001). The following linear features classes were transformed to polygons by buffer procedure:

- motorways, streets
- (active) railways
- water courses with a width > 6 m or used for shipping

The individual buffer size was determined from the recorded width or rather width class of line elements. Missing information was replaced by mean width of the specific feature type.

The degree of woodland fragmentation was calculated for the reference level 'Borders of topographic map sheets on a scale of 1:25000' (TK25). A binary 'woodland vs. non-woodland'-map was generated for each map sheet (2947 units) by the cutting-out procedure, as polygons were directly intersected with the reference level data (compare with Moser et al., 2007). All 19 landscape metrics were calculated for each map sheet.

In addition to woodland geometries for calculation of landscape indices we required occurrence data of the species, which could be used as input for the habitat modelling. We were granted access to presence data of the species which are based on map sheets of the topographic map on a scale of 1:25000 (TK25) from the German Federal Agency of Nature Conservation (BfN).

Data preparations were done by means of GIS software ArcGISTM Desktop (ESRI) and PostGIS tools (Refractions Research). A PostgreSQL database was used for data management and indices calculation.

¹Amtlich Topographisch-Kartographisches Informationssystem (the official digital topographic maps of Germany)

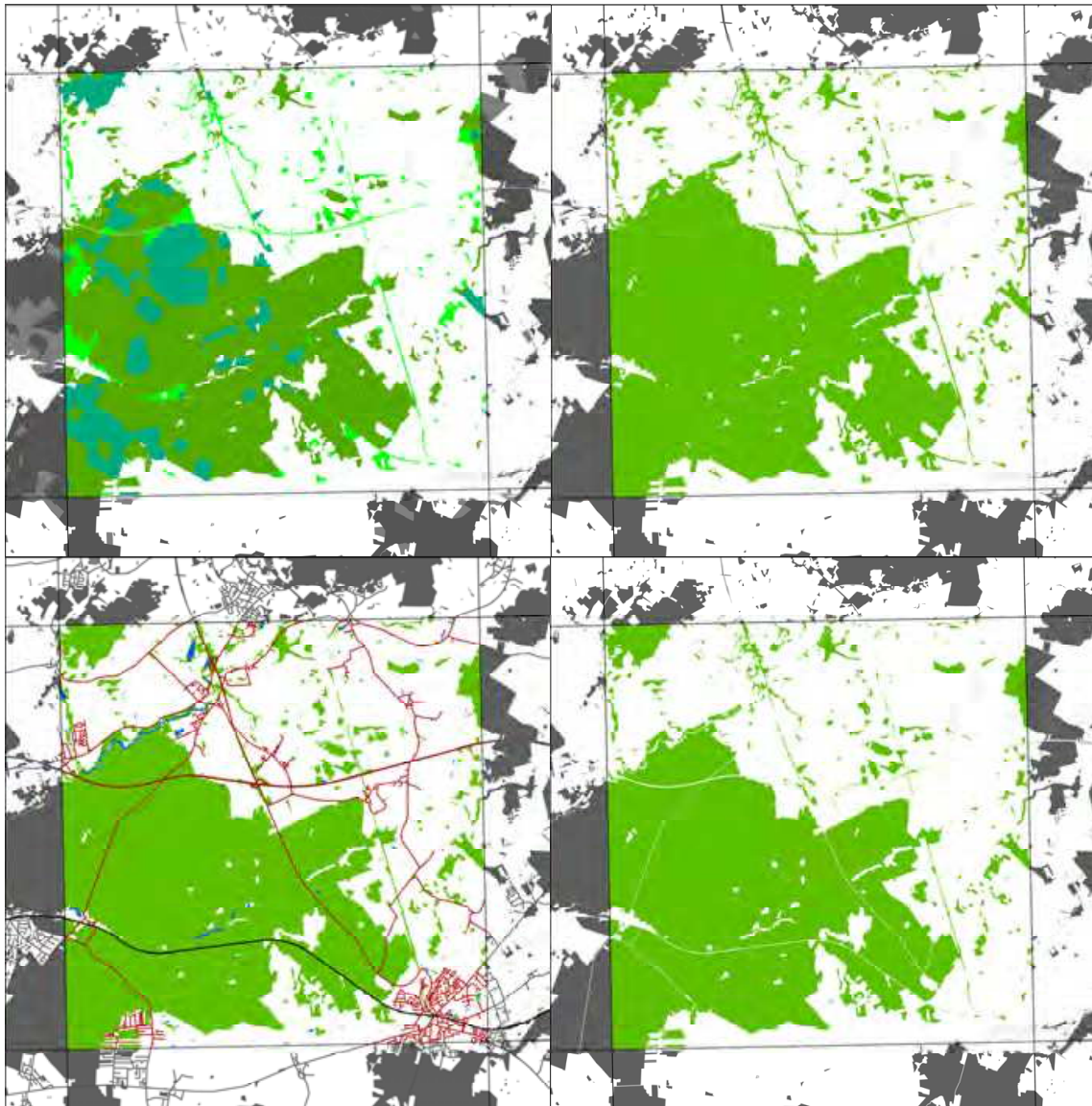


Fig. 1. All pictures show landscape elements in map sheet TK2428. top left: forest types. top right: aggregated forest. lower left: aggregated forest and transportation lines. lower right: binary forest map with separated forest areas.

2.3 Selected species

For the habitat models we chose the barbastelle bat *Barbastella barbastellus*, the black stork *Ciconia nigra*, the European wildcat *Felis silvestris*, Bechstein's bat *Myotis bechsteinii*, and the stag beetle *Lucanus cervus*. The selected species are all of high interest for nature conservation as species of the EU Habitat Directive (FFH) or the Conservation of Wild Birds Directive (The Council of the European Communities, 2004). They all occur in woodlands with special structures and have very different dispersal abilities.

B. barbastellus can rarely be found in woodland areas smaller than 1 km². Its home range sizes have strong variations (1.25-25 km²: Hillen et al., 2009; home range diameter 4-5 km: Russo et al., 2004; Steinhauser, 2002), but compared to *M. bechsteinii* it is able to cross motorways (Kerth & Melber, 2009).

M. bechsteinii occurs in mature, natural woodland areas of at least 2.5-3 km² (Kanuch et al., 2008). Home range sizes vary from 1 km² (Kerth & Morf, 2004; Kerth et al., 2001) to diameters of 3 km (Steinhauser, 2002). In fragmented woodland areas home range sizes of *M. bechsteinii* increase, which leads to a lower probability of survival (Norberg & Rayner, 1987; Siemers & Swift, 2006).

The highly specialised species *C. nigra* occurs only in undisturbed deciduous woodlands (> 80 % deciduous trees). Additionally, the distance to the next water body should not exceed 1 km (Augutis & Sinkevicius, 2005). The main threat to this species is habitat degradation because of deforestation (particularly the destruction of large traditional nesting trees), the rapid development of industry and farming, and the building of dams and lake drainage for irrigation and hydroelectric power production (BirdLife International, 2009; Rosenvald & Lohmus, 2003). The absence of disturbances is one of the main predictions for the occurrence of *C. nigra*.

The European wildcat (*F. silvestris*) only occurs in large and undisturbed areas. Home range sizes fluctuate from 0.7-14 km² (females) to 2-50 km² (males; Monterroso et al., 2009). *F. silvestris* avoids approaching areas of settlement, e. g. it is known to make detours of a distance up to 900 m for a small village and 200 m for a single house (Klar et al., 2008).

L. cervus lives in large, unbroken oak woodlands. Its occurrence depends mainly on the presence of dead wood (Pratt, 2000). Home range sizes vary from 0.2 ha (females) to 1 ha (males) and cover distances of 1 km (females) to 3 km (males; Rink & Sinsch, 2007; Sprecher-Uebersax, 2003).

2.4 Habitat models

Niche models of these species were calculated to show the impacts of woodland fragmentation on different woodland species. These models can be used to expose potential habitats that are not yet colonised.

We analysed the suitability of the abovementioned landscape metrics to predict the occurrence of threatened species. We used the selected landscape metrics as environmental variables for the habitat models. Accordingly, 19 landscape metrics were calculated for each of the 2947 map sheets covering the territory of the Federal Republic of Germany. To generate the habitat models a correlation analysis is necessary to exclude variables with an absolute value of the correlation coefficient higher than 0.7 (Fielding & Haworth, 1995; Schröder & Reineking, 2004).

Predictive distribution modelling was done with the software program Maxent (Vers. 3.3.3). Maxent was developed by the machine learning community and uses a statistical technique called maximum entropy that generates a prediction from incomplete information (Phillips et al., 2006; Phillips et al., 2004). Adopting this method, 100 iterative models per species were created. In each cycle, Maxent was configured in such a way that 75 % of the total presence records were used to train the models and 25 % were reserved to test the resulting models. Logistic output format was chosen.

All other statistical analysis was done using R (R Development Core Team, 2010) and SPSS 17 (IBM).

3. Results

3.1 Landscape indices

Besides the geo data and thematic input layers the results of the indices calculation are stored in a PostgreSQL-database. Unambiguous keys enable us to link the results with the reference level ‘TK25’ map sheets.

The calculated landscape indices for each single map sheet are the input layers for the habitat models. The distribution of the landscape metrics at reference level ‘TK25’ is described by the means of descriptive statistical quantities. Mean, standard deviation, minimum and maximum values are shown in table 1. These values identify the statistical distribution of indices calculated from the binary ‘woodland/non-woodland’-landscapes in 2947 map sheets.

Landscape metrics	MEAN	SD	MIN	MAX
TA (km²)	129.73	7.05	7.90	176.92
CA _f (km²)	38.57	26.40	0.00	129.60
PLAND _f	0.29	0.20	0.00	0.96
NP _f	250.90	139.09	0	832
PD _f (1/km²)	1.94	1.07	0.01	6.44
PD _{ff} (1/km²)	15.60	36.34	0.05	1257.26
MPS _f (km²)	0.22	0.44	0.00	19.15
LPI _f	0.08	0.09	0.00	0.66
MESH (km²)	2.71	5.59	0.00	61.39
MPAR (km/km²)	104.68	129.05	26.64	5431.75
MSI	1.81	0.23	1.12	3.59
AWMSI	0.93	0.85	0.00	7.60
LSI	9.10	4.40	0.00	25.92
MPFD	1.41	0.11	1.22	5.05
TE (km)	368.92	180.70	0.00	1056.38
ED (km/km²)	2.82	1.35	0.00	8.09
MENN (km)	0.11	0.81	0.00	43.51
TLD _S (km/km²)	1.92	1.30	0.00	12.87
TLD _R (km/km²)	0.08	0.17	0.00	2.25

Table 1. Descriptive statistics of selected landscape indices at reference level ‘TK25’

Total area (TA) and forest area (CA_f) represent the reference values for several other landscape metrics calculated for each map sheet. The fragmentation composition can be described with following metrics: number of patches (NP_f), mean patch size (MPS_f), largest patch index (LPI_f), patch density (PD_f, PD_{ff}), and effective mesh size (MESH). Other indices, like shape index (MSI, AWMSI, LSI), mean area-perimeter-ratio (MPAR), or mean patch fractal dimension (MPFD), characterise the shape of fragmentation. Patch fragmentation indices, like distance to nearest neighbour (MENN), describe connectivity/isolation of patches in the map sheets. Transport line density (TLD_S, TLD_R) was derived from the length of linear elements and was not directly comparable with edge metrics (TE, ED) which include all borders of patches (for specified descriptions see annex).

The following figures show selected landscape indices as spatial distribution grid maps, as measures are based on comparable sizes of reference units (map sheets).

Figure 2 represents a typical forest map of Germany illustrating the spatial extent of the index 'percentage of forest in landscape' ($PLAND_i$).

Figure 3 allows comparison with the landscape index 'effective mesh size' (MESH) for woodlands in Germany. MESH provides a relative measure of patch structure and is interpreted as the size of the areas when the region under investigation is subdivided into areas of the same size and with the same degree of landscape division (Jaeger, 2000; McGarigal & Marks, 1995). High values (maximum about 61 km²) describe large, contiguous forest areas (e. g. in the Alps or the low mountain ranges), whereas small measures identify a low percentage of forested area and highly fragmented woodlands respectively (e. g. coastal regions or the central lowland in Saxony-Anhalt).

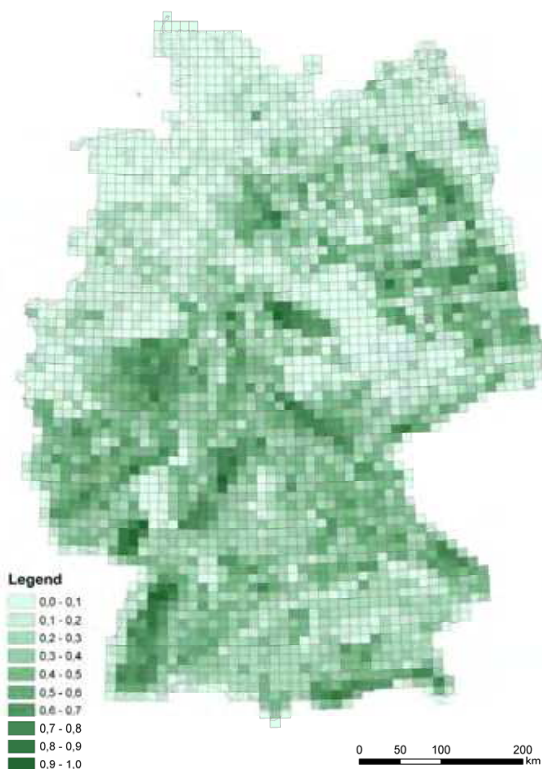


Fig. 2. Spatial distribution of 'percentage of forest area' ($PLAND_i$) in Germany

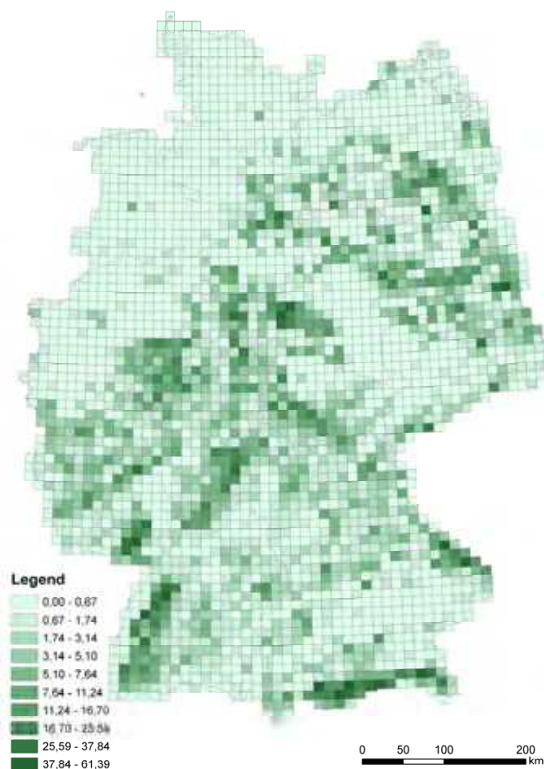


Fig. 3. Spatial distribution of 'effective mesh size' (MESH in km²) of woodland in Germany

The 'mean shape index' (MSI), a simple and straightforward measure of overall shape complexity, is shown in figure 4. The value increases as the mean patch shape becomes more irregular (McGarigal & Marks, 1995), e. g. in some regions in Baden-Württemberg or North Rhine-Westphalia.

Figure 5 displays the 'mean Euclidean distance to the nearest neighbour' (MENN) of woodland patches at reference level 'TK25'. In regions with small percentages of forest area,

e. g. lowlands in central Germany or the North Sea coast, MENN extends to a maximum of 43 km. At the other hand, in heavily forested areas, e. g. low mountain ranges, only marginal values < 0.1 km can be observed.

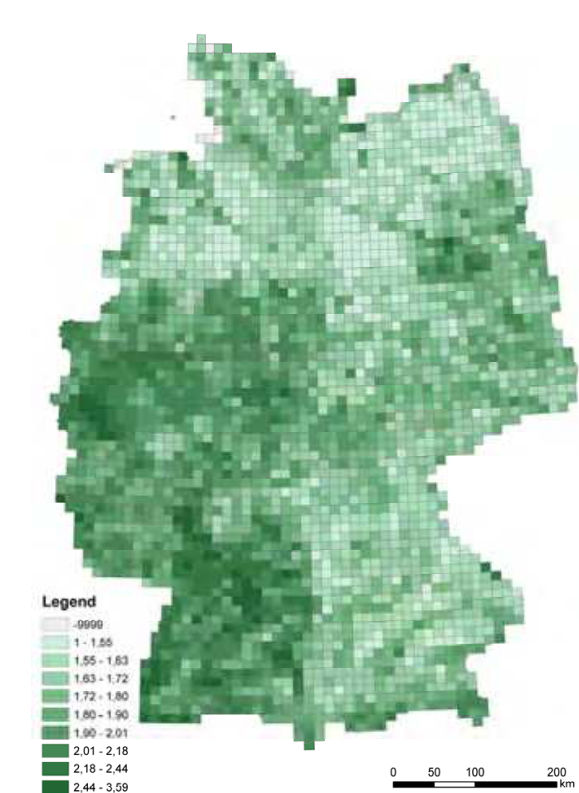


Fig. 4. Spatial distribution of ‘mean shape index’ (MSI) of woodland patches in Germany

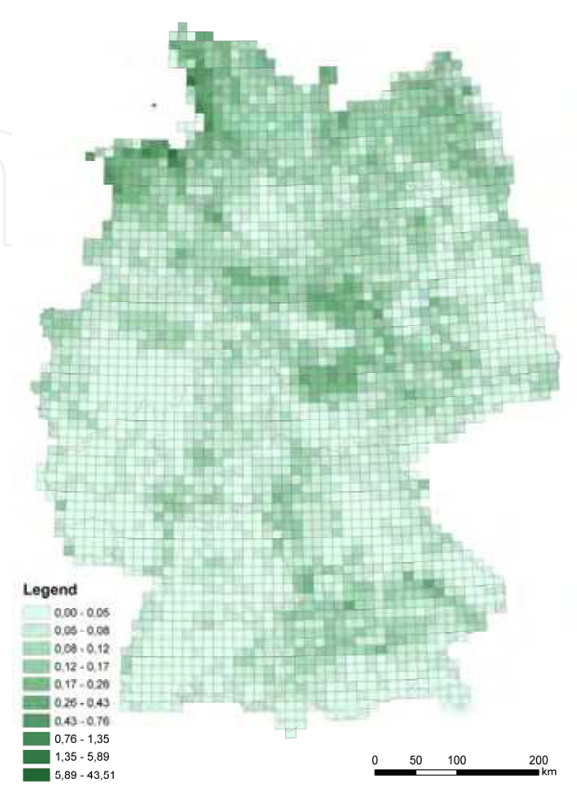


Fig. 5. Spatial distribution of ‘mean Euclidean distance to nearest neighbour’ (MENN in km) of woodland patches in Germany

3.2 Model results

After the correlation analysis we calculated a model with the following landscape metrics: MENN, MESH, MPAR, MPFD, MSI, NP_f, TLD_S, und TLD_R. Table 2 shows a summary of the habitat model results of the analysed species.

species	pattern quality (AUC) ± standard deviation	most important variable in the model	second important variable in the model
<i>Barbastella barbastellus</i>	0.764 ± 0.011	MESH	MSI
<i>Ciconia nigra</i>	0.832 ± 0.011	MESH	TLD _S
<i>Felis silvestris</i>	0.889 ± 0.008	MESH	MSI
<i>Lucanus cervus</i>	0.777 ± 0.009	MSI	MESH
<i>Myotis bechsteinii</i>	0.761 ± 0.009	MESH	MENN

Table 2. Summary of the model results of the different species.

The results demonstrate that there is a relationship between species' occurrences and calculated landscape metrics. Fragmentation indices like the 'effective mesh size' and the 'mean Euclidean distance' to the next woodland patch and metrics concerning the shape of woodland patches (MSI) are particularly predictive of species occurrences. The occurrence probability of *C. nigra* also depends on the 'transportation line density' of streets (TLD_s). The best occurrence probability was calculated in the models of *C. nigra* and *F. silvestris*. Both model results show higher AUC-values (area under the curve) than 0.8, which signifies models with 'good' predictive power (Reineking & Schröder, 2004).

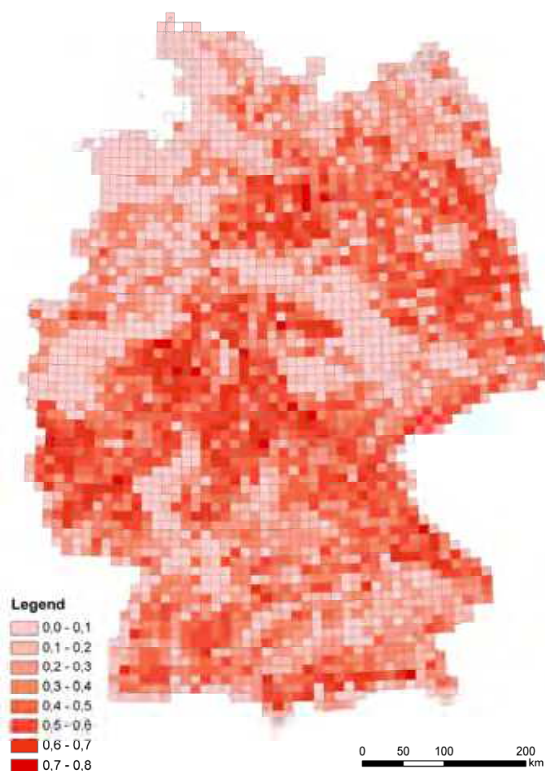


Fig. 6. Habitat model results of *C. nigra*.

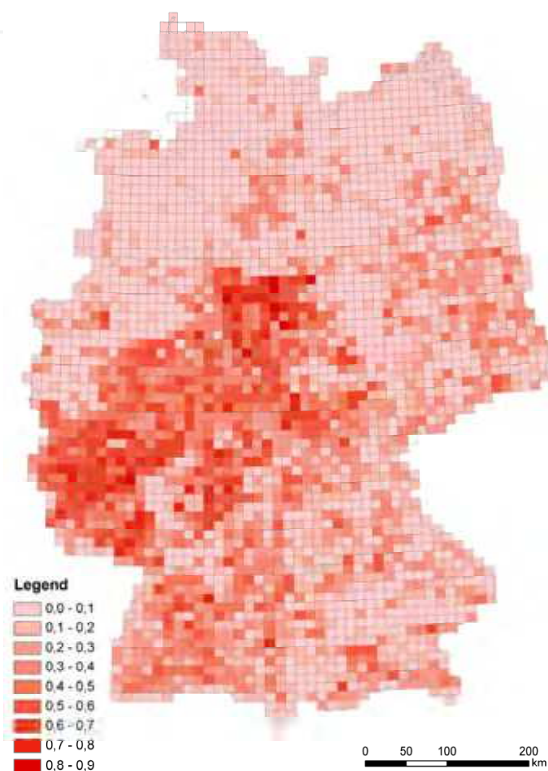


Fig. 7. Habitat model results of *F. silvestris*.

The map of the model results of *C. nigra* (figure 6) shows that the highest occurrence probability is correlated with densely wooded areas in Germany. Following the map, the black stork occurs in all lower mountain ranges (in central Germany) and in sparsely populated areas (in Mecklenburg-West Pomerania and Brandenburg).

The map of the wildcat's model results (figure 7) shows that occurrence probability is low in the northern parts of Germany and highest in the low mountain ranges in central Germany.

The model results of the three other species have been 'acceptable' indicated by AUC-values above 0.7 (Reineking & Schröder, 2004). The maps of the models reveal less obvious results than the results of *C. nigra* and *F. silvestris* present. These model results are shown in figure 8 - 10. Compared to the Bechstein's bat and the stag beetle, the barbastelle bat is more orientated to the eastern part of Germany. The Bechstein's bat and the stag beetle show higher occurrence probabilities in the southwest.

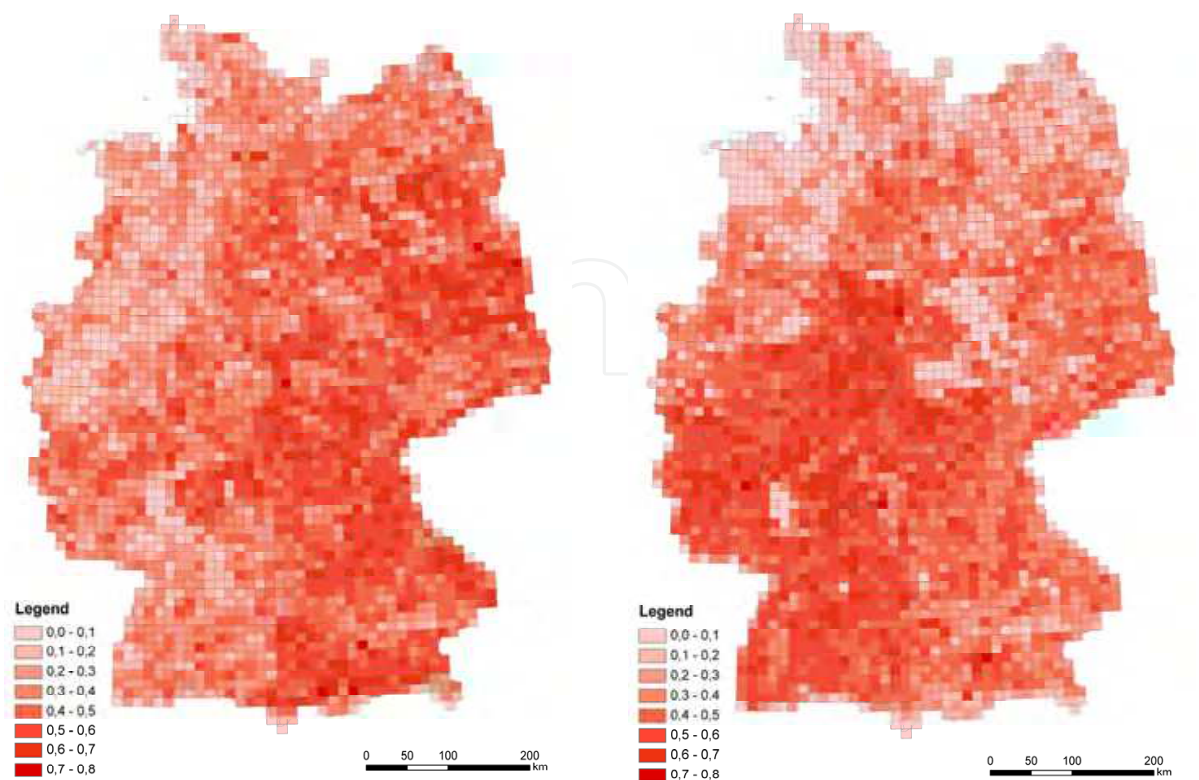


Fig. 8. Habitat model results of *B. barbastellus*. Fig. 9. Habitat model results of *M. bechsteinii*.

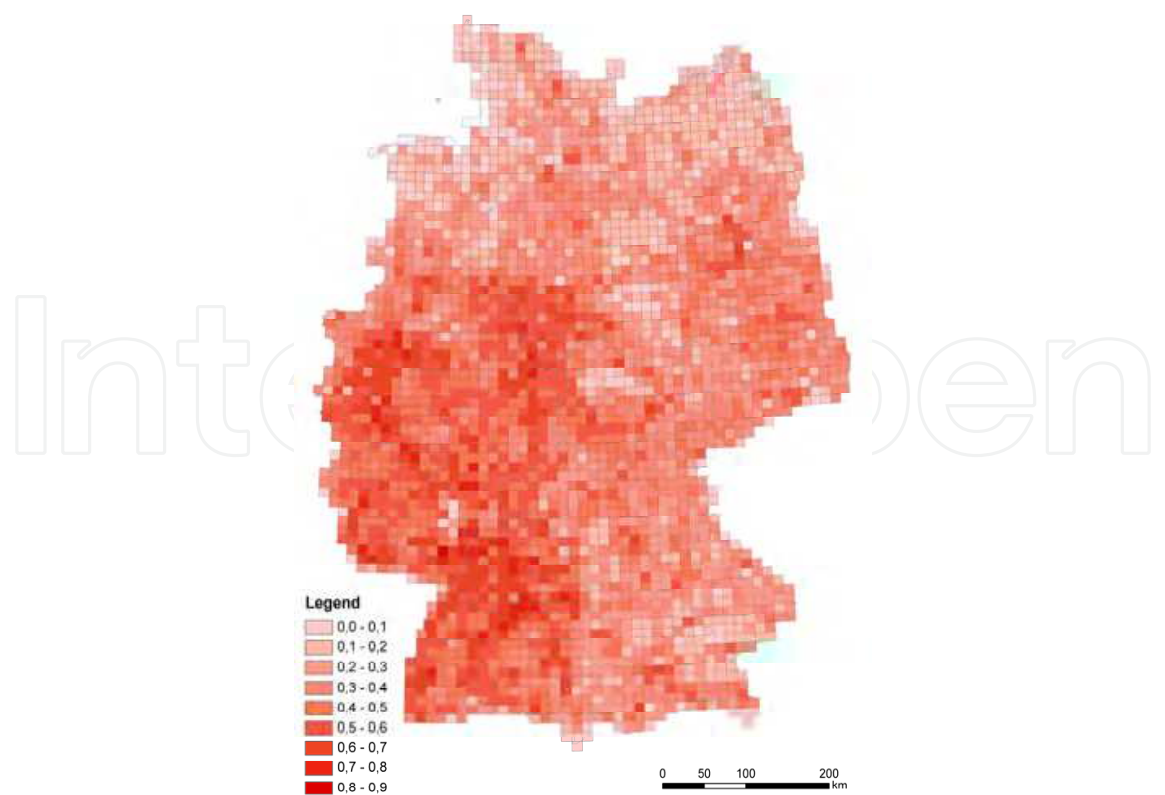


Fig. 10. Habitat model results of *L. cervus*.

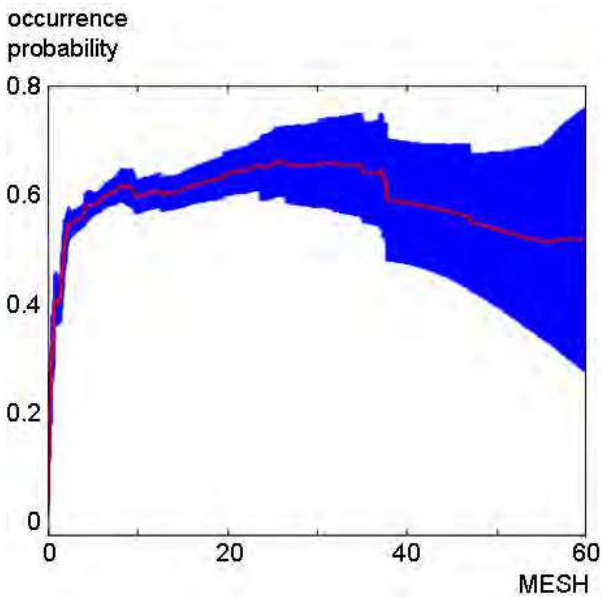


Fig. 11. Response of the occurrence of *F. silvestris* dependent to the 'effective mesh size' (MESH in km²; standard deviation is coloured in blue).

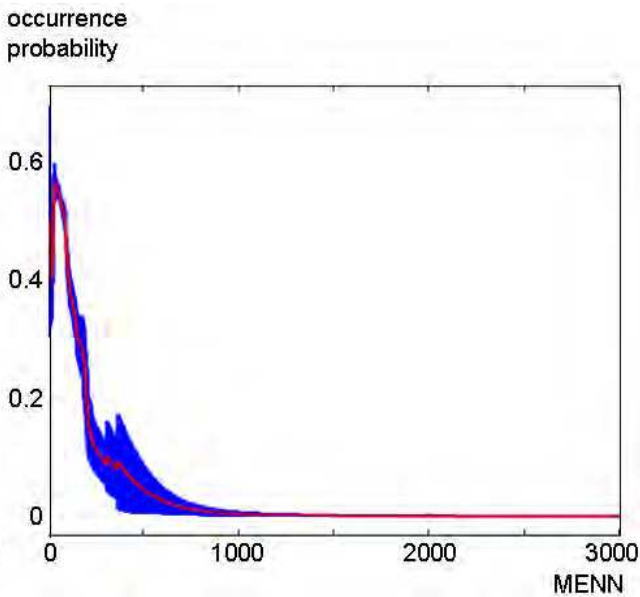


Fig. 12. Response of the occurrence of *M. bechsteinii* dependent to the 'mean Euclidean distance to nearest neighbour' (MENN in m) of woodland patches (standard deviation is coloured in blue).

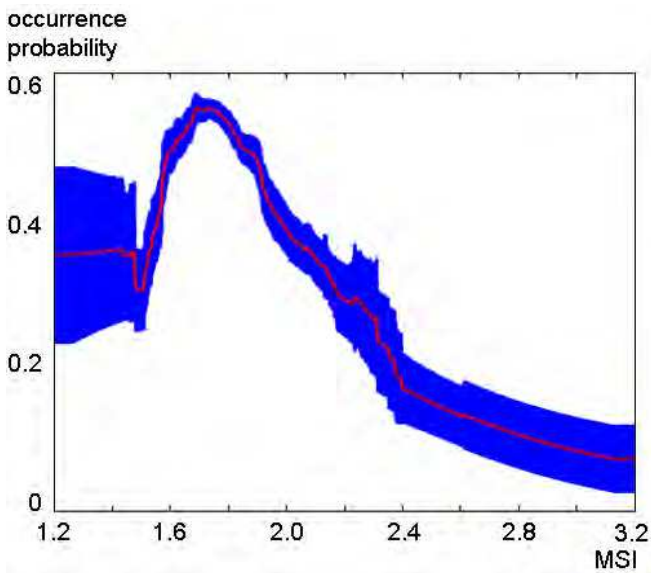


Fig. 13. Response of the occurrence of *B. barbastellus* dependent to the 'mean shape index' (MSI; standard deviation is coloured in blue).

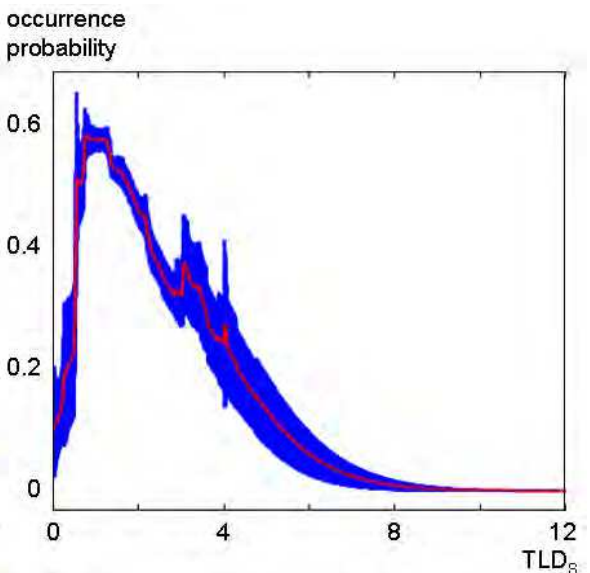


Fig. 14. Response of the occurrence of *C. nigra* dependent to the 'transportation line density of streets' (TLD_s in km/km²; standard deviation is coloured in blue).

The landscape metrics with the highest influence in the model have also been comparable: The occurrence probabilities of *F. silvestris*, *M. bechsteinii*, *C. nigra*, and *L. cervus* were highest if MESH reaches mean values (compare results of *F. silvestris* in figure 11). The index 'mean Euclidean distance to nearest neighbour' of woodland patches. is also critical for the occurrence probability of the species (compare figure 12). The closer the neighbouring woodland patches (= the lower the MENN values), the higher is for example the occurrence probability of *M. bechsteinii*. The occurrence probabilities of *B. barbastellus*, *L. cervus*, and *F. silvestris* concerning the woodland structure are high if the 'mean shape index' (MSI) indicates medium values (for *B. barbastellus* see figure 13). Furthermore, the response of the occurrence probability of *C. nigra* to the 'transportation line density of the streets' shows that the probability declines with increasing density of streets (figure 14).

4. Discussion

In this study we investigated the shape, pattern, and the fragmentation status of the German woodlands by landscape metrics and analysed the impacts of fragmentation on different FFH species' occurrences.

4.1 Landscape metrics for predicting species occurrences

The results of our habitat models show that it is possible to predict species occurrences with measures of landscape structure concerning habitat fragmentation.

The presence of the selected species can be described by different landscape metrics like MESH, MENN, MSI and TLDs. The contribution to habitat suitability of the predictors in the final model reflects the understanding of the ecology of our target species. As expected, the presence of forest habitats was an important determinant of suitability for the selected target species, but considering and comparing the different species we can assume that not only large woodland areas are essential for their occurrences. Comparing the maps of the habitat models with the map of the woodland area (figure 2) there is only the model of *C. nigra* which shows higher congruencies.

F. silvestris depends on large undisturbed areas but it also needs special woodland structures (mean MSI results in high occurrence probabilities) because low distances to e. g. woodland edges and rivers result in higher densities of prey (Doyle, 1990; Gomez & Anthony, 1998; Osbourne et al., 2005). The same holds true for species like the barbastelle bat. It also depends on large woodland areas but has its foraging grounds at woodland edges (Kerth & Melber, 2009; Norberg & Rayner, 1987; Steinhauser, 2002). *L. cervus* has less power of dispersal than the other selected species. It needs large amounts of dead wood in more or less undisturbed woodlands (Pratt, 2000) and covers distances up to 3 km (males; Rink & Sinsch, 2007). The model results of *L. cervus* are to be considered with care, because in fact data of smaller scales (presence data and landscape metrics) is necessary to calculate more significant models (compare Garcia-Gigorro & Saura, 2005; Wu, 2004).

The importance of fragmentation indices (like MESH, MENN and TLDs) in the model results shows the general sensitivity of the analysed species to fragmentation due to their ecological traits (like high trophic level, large home range sizes or low dispersal ability). Like

other studies show, we can confirm that simple fragmentation components have higher influences on species occurrences than more complex ones (compare Fischer et al., 2004; McGarigal & McComb, 1995; Rutledge & Miller, 2006).

Landscape metrics are important tools to quantify the fragmentation, but most of them have only limited explanatory power for ecological processes because of their potential for inconsistent and ambiguous statistical relationships with response variables of ecological processes (Tischendorf, 2001). However, spatial pattern analysis should be used to explain structural changes in landscape and consider ecological processes (Li & Wu, 2004). Linking fragmentation metrics with the occurrence of species is one important step, but we need additional data, like information about habitat quality, to improve the understanding of spreading of animals, pattern quality, and the model's explanatory power. Consequently, as accentuated by our results for our target species, the landscape structure is an important aspect to be considered in defining patterns of habitat suitability.

Our methods could be used as a framework and forms a basic concept for further research. Furthermore, our approach could be extended to other fragmentation-sensitive species.

4.2 Possibilities for nature conservation

The combination of landscape metrics and habitat suitability for species results in a methodology that improves the potential for understanding patterns of species distribution.

There is no doubt that preservation and restoration of large undisturbed areas are priorities for conservation of many species (e. g. Drees et al., 2011). Mortelliti et al. (2011) confirm this and add that structural connectivity is necessary and should not be regarded without the amount of available habitat in landscapes. However, structural connectivity should also be considered in conjunction with habitat quality, which is strongly driven by species-specific determinants (Mortelliti et al., 2010).

Accordingly, the main aims should be to map potential habitats that are adapted to different scales (depending on species selection) in combination with habitat quality to develop a connected habitat system. This is especially true because global warming contributes to fragmentation of landscapes. Species that are unable to disperse will become extinct because they may live in restricted geographical ranges and are unable to reach disconnected ecological niches or other intact habitats (compare Habel et al., 2010).

Linking landscape metrics with species' occurrences can be an important step to support the development of management plans for conservation.

5. Conclusions

The behaviour of species concerning landscape configuration is generally very complex. Consequently, estimating and calculating patterns based on models are quite difficult.

However, combining landscape structure with the presence of species could be a feasible approach for the quantification of landscape-species relationships and thus, could provide a foundation for studies on regional and/or local scales. Additionally, this methodology may give new insight into nature conservation and landscape management practices.

6. Acknowledgments

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7. Annex

Landscape metric	equation	Result space/unit
Total area (reference unit)	$TA = \frac{A}{1000000}$	$TA > 0$, km ²
Total class area (forest)	$CA_f = \frac{\sum_{j=1}^n a_{ij}}{1000000}$	$CA_f \geq 0$, km ²
Percentage of landscape (forest)	$PLAND_f = \frac{CA_f}{TA}$	$0 \leq PLAND_f \leq 1$
Number of patches (forest)	$NP_f = n_i$	$NP_f \geq 0$
Patch density (reference to total area)	$PD_f = \frac{n_i}{TA}$	$PD_f \geq 0$, n/km ²
Patch density (reference to total class area)	$PD_{ff} = \frac{n_i}{CA_f}$	$PD_{ff} > 0$, n/km ²
Mean patch size (forest)	$MPS_f = \frac{CA_f}{n_i}$	$MPS_f > 0$, km ²
Largest patch index (forest)	$LPI_f = \frac{\sum_{j=1}^n \max(a_{ij})}{1000000 \times TA}$	$0 \leq LPI_f \leq 1$
Effective mesh size (forest)	$MESH = \frac{\sum_{j=1}^n \frac{a_{ij}^2}{1000000}}{TA}$	$0 \leq MESH \leq TA$, km ²
Mean perimeter-area ratio (forest)	$MPAR = \frac{\sum_{j=1}^n \frac{p_{ij}}{a_{ij}} \times 1000}{n_i}$	$MPAR > 0$, km/km ²

Landscape metric	equation	Result space/unit
Mean shape index (forest)	$MSI = \frac{\sum_{j=1}^n \left(\frac{p_{ij}}{2\sqrt{\pi * a_{ij}}} \right)}{n_i}$	$MSI \geq 1$
Area-weighted mean shape index (forest)	$AWMSI = \sum_{j=1}^n \left[\left(\frac{p_{ij}}{2\sqrt{\pi * a_{ij}}} \right) \left(\frac{a_{ij}}{\sum_{j=1}^n a_{ij}} \right) \right]$	$AWMSI \geq 1$
Landscape shape index	$LSI = \frac{\sum_{k=1}^m e_{ik}}{1000 \times 2\sqrt{\pi * TA}}$	$LSI \geq 1$
Mean patch fractal dimension	$MPFD = \frac{\sum_{j=1}^n \left(\frac{2 \times \ln(p_{ij})}{\ln(a_{ij})} \right)}{n_i}$	$1 \leq MPFD \leq 2$
Total edge (without landscape boundary)	$TE = \frac{\sum_{k=1}^m e_{ik}}{1000}$	$TE \geq 0, \text{ km}$
Edge density (without landscape boundary)	$ED = \frac{\sum_{k=1}^m e_{ik}}{1000 \times TA}$	$ED \geq 0, \text{ km/km}^2$
Mean nearest-neighbour distance (forest)	$MENN = \frac{\sum_{j=1}^n \min d_{jg}}{1000 \times n_i}$	$MENN \geq 0, \text{ km}$
Transportation line density (streets/railways)	$TLD = \frac{\sum_{k=1}^m l_{ik}}{1000 \times TA}$	$TLD \geq 0, \text{ km/km}^2$

Table 3. Landscape metrics – equations and result space (Jaeger, 2000; McGarigal & Marks, 1995).

Notation:

A	total area (m ²) of landscape (TK25 map sheet)
a _{ij}	area (m ²) of patch i _j
d _{ijg}	distance (m) between patch j and g of class i
e _{ik}	total length (m) of edge in landscape involving patch type (class) i
l	length (m) of line elements of class i (streets/railways)
n _i	number of patches in landscape of class i
p _{ij}	perimeter (m) of patch i _j

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