Analysis of historic landscape patterns with a Geographical Information System – a methodological outline

Felix Kienast

*Swiss Federal Institute of Forest Snow and Landscape Research (FSL), Dept. of Landscape Ecology,
8903 Birmensdorf, Switzerland*

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Abstract

Various methods for storing, retrieving, and analyzing historic land use records by means of electronic data processing are evaluated. The procedures are illustrated with data from a pilot study on the Swiss Plateau which is part of a broader landscape historical monitoring program at the Swiss Federal Institute of Forest, Snow and Landscape Research. The land use matrix was derived from topographic maps, aerial photographs and other land use records and spans approximately 100 yrs with an updating cycle of 7 to 20 yrs. A special technique was developed to generate series of digital maps and to superimpose the data layers of various time steps. Each landscape element is described with time-stamped attributes to ensure access to the entire "life history" from any point in space or time. The proposed data model proved to be a powerful tool for routine updating of digital maps. It can be used by practitioners as well as scientists working with Geographical Information Systems (ARC/INFO or similar package). With this procedure, disturbance maps over any number of available updates can be quickly generated, allowing the user to identify zones of similar degrading or upgrading tendency. The procedures for analyzing changing landscape structures include calculation of information theoretic indices (diversity, dominance), calculation of fractals, edge analysis, as well as landscape assessment along random traverses. The latter proved to be especially powerful, where barrier/habitat frequencies were evaluated. On the basis of all parameters calculated, landscape structures on the study plot seem to be ecologically most favorable in the 1930's followed by a strong degradation in the World War II- and the post-World War II period. In contrast to many hypotheses, the landscape structures in the second half of the 19th century were structurally less favorable than between 1900 and 1930.

Introduction

In analogon to the island biogeographic model of MacArthur and Wilson (1967) landscapes are often described as patterns of habitat islands that are connected through a network of barriers and corridors. Corridors are assumed to allow movement and genetic exchange between animal and plant populations, whereas barriers seem to inhibit such an exchange (Forman and Godron, 1986). Although the

biogeographic model of MacArthur and Wilson (1967) has been applied to patches on land with limited success, numerous landscape restoration plans and nature protection bills are based on its principles (Wildi *et al.*, 1990). Thus, the scientific background of how landscape networks are really functioning and to which degree connectivity is needed for genetic exchange, has yet to be established (Forman and Godron, 1986). It is undisputed that the actual land use pattern of a region has a

Fig. 1. Study area near Inwil (Canton Luzern) in two different time steps. The topographic maps date from 1888 (upper) and from 1982 (lower), and originate from two map series with different survey methods (reproduced with permission of the Federal Office of Topography of November 14, 1991).

strong influence on a variety of ecological phenomena such as net primary production (Woodwell and Whittaker, 1968) and horizontal movement of plant and animal populations (Dansereau, 1957; Swingland and Greenwood, 1983). However, the actual status of a landscape is merely a snapshot of a century-old land use evolution, and the historic

development of a region is often one of the most decisive factors, if not the most important, governing species distribution of plants and animals (Schwaar, 1972; Semotanova, 1988; Sheail, 1986; Willerding, 1988). Consequently many landscape restoration plans rely on historical land use records as an important source of information and there is

a growing research field for landscape historians to provide easily accessible information on historical land use changes (Iverson, 1987, 1988; Kopp *et al.*, 1982; Pedrolí and Borger, 1990).

With the technical breakthrough in the field of Geographical Information Systems, handling and analyzing of digital spatial data can be done most effectively (Burrough, 1990a; O'Neill *et al.*, 1988; Smith *et al.*, 1987). Recent publications (Donovan *et al.*, 1987; Johnson, 1990; Young *et al.*, 1987) suggest that Geographical Information Systems (GIS) are increasingly applied to perform habitat analysis to assess potential species abundance from land use data. Nevertheless many GIS have only limited functionality for analyzing historic land use data due to missing tools for handling the temporal component of spatial information (Burrough, 1990b). On the theoretical level, several papers have been published on the design of spatio-temporal datasets (Armstrong, 1988; Langran, 1989; Price, 1989; Vrana, 1989). However in practical applications (i.e. biotope inventories by Governmental agencies) these findings do not seem to be disseminated sufficiently, and digital maps of different time steps are too often stored like traditional map sheets; each on top of the other and without access to the temporal component.

The main purpose of the present paper is to evaluate various methods for analyzing landscape patterns over space and time by means of electronic data processing. Thus, it provides a methodological guideline for both researchers and practitioners that are working with spatio-temporal data sets, in particular with regularly updated inventories of landscape resources. All methods presented in this paper are illustrated with data from a pilot study in Switzerland (Figure 1), which is part of a broader landscape historical monitoring program at FSL to assess landscape changes in Switzerland over the last 100 yrs. Similar studies were carried out by Turner (1987, 1990) in a very comprehensive statistical analysis of changing landscapes in Georgia (USA) by means of aerial photographs. Incorporation of historical map series into a GIS has, for example, been demonstrated by Iverson (1988) and Hodgson and Alexander (1990).

Data sources

For many countries topographic maps in the scale of 1:20'000 to 1:30'000 provide reliable monitoring data over the last 100 to 150 yrs (Hodgson and Alexander, 1990). Additionally, there are often rich collections of detailed plans in larger scales (1:5000 to 1:500) that date back to the late 18th and the early 19th century (Dürst, 1990; Müller, 1990). For the present study the main data sources are two series of topographic maps in the scale of 1:25'000 dating back to the 1880's. An example of each map series is given in Figure 1. The updating interval of the maps is 7 to 20 yrs depending on the period considered. Each modification cycle is documented extensively in the topographic field notes and since the 1930's in the aerial photointerpretation of the Swiss Federal Office of Topography. For the study area presented in this paper a total of 12 time steps could be processed. Thirteen land use types were monitored routinely, eleven over approximately 100 yrs and two over approximately 40 yrs. The land use types include transportation (footpaths, roads, freeways, railway tracks), streams, rivers, wetlands, closed and open canopy forest, hedg-crows, industrial complexes, gravel pits, and residential areas.

Since topographic maps are perceptions of the environment and often rather a 'text than a mirror of reality' (Harley, 1989), definition of specific landscape elements or habitat types may vary considerably over time and the location of features is often less accurate in earlier map editions compared with today's standards (Hodgson and Alexander, 1990). Some of these misinterpretations are impossible to correct. However with a strict crossdating and a comparison of the historic maps with data from independent sources, most incompatibilities were eliminated. This was accomplished by consulting the written protocols and field notes of the topographers. Maps that were produced after 1930 could be verified with vertical aerial photographs.

Methods

The land use data were digitized from analog maps using a Tectronix digitizing tablet. Data processing

was performed on a Tectronix-4336 computer using UNIX. The Geographical Information System ARC/INFO as well as commercial graphics and statistics programs were used to perform the analyses.

Spatio-temporal data model. To generate the spatio-temporal data matrix all landscape elements of the first map edition were digitized. Subsequent layers were generated by copying and modifying the previous covers according to the changes documented in the original field notes (and since 1930 in the aerial photointerpretation) of the Swiss Federal Office of Topography. They render evidence about all landscape changes that were detected between two map updates. After generating a data cover for each time step routine overlay techniques were used to merge the various layers to one composite cover (Figure 2). Depending on the complexity of the land use changes, initially homogeneous patches are subdivided into numerous spatial elements that are characterized with time-stamped attributes featuring the land use history over time. New elements that are established on only a part of a formerly homogeneous spatial element can be handled as easily as spatial elements that never changed their geometry. The total number of patches of the unified cover is equivalent to the least common multiple of all spatial objects in the individual layers. Thus the entire life cycle of each landscape element considered can be accessed from any time step. The data model is able to quickly generate the landscape pattern of a specific time step or to calculate differences between two or more updates. Thus the method fulfills all requirements of a spatio-temporal database as claimed by Price (1989). The data model is described in detail in Kienast *et al.* (1991).

Landscape indices. Landscape patterns can be characterized by means of statistical indices as suggested by Footpath *et al.* (1988), O'Neill *et al.* (1992) and Turner (1990). In the present analysis the following landscape indices were calculated:

- diversity (H) (formulae 1 and 2, Appendix)
- dominance (D) (formula 3, Appendix)
- amount of edge between land use types
- fractal dimension (d) of land use patches (formula 4, Appendix)

Fig. 2. Example of a spatio-temporal data model. Routine procedures of the GIS software ARC/INFO have been used to update, modify, and finally merge the data layers of various time steps. Each spatial object of the unified data cover (least common multiple of all time steps) is characterized with time-stamped attributes to ensure full access of the temporal component.

The fractal dimension can be used to estimate the complexity of the geometry of land use patches. In accordance with Gardner *et al.* (1987) and Lovejoy (1982) the fractal dimension, d , was estimated by linear regression analysis using formula 4 (Appendix).

Traverse analysis. In addition to the landscape analyses employing information theoretic indices, landscape structures can also be assessed by means of different sampling techniques. A powerful

Fig. 3. Landscape assessment by means of traverse analysis. The random paths are divided into 25 m segments. In each segment presence or absence of land use types are recorded. Segments outside the mapped area are excluded from the data set. For further details see text.

method is sampling along lines and recording all landscape elements that occur in segments of a given length (Forman and Godron, 1986; Godron and Bacou, 1975; Kershaw, 1958; Paget and Godron, 1982; Poissonet *et al.*, 1973). In our study we used this technique to determine distances between habitats of different ecological value as well as frequencies between habitats and barriers. Barriers are landscape elements with a minimum of life requisites (i.e. food, cover, shelter) for animals and plants. The method of sampling along lines resembles the network method described by Lupien *et al.* (1987). However, the route that is determined is not an optimal path in terms of least distance, but rather an artificially given path. In the present study two types of traverses are applied, namely moving along systematic grid lines, and moving along random paths (Figure 3). Each random route has an individual length of 2.5 km and consists of 100 segments of 25 m length. Starting point is a random point with a random azimuth. After the 20th, 40th, 60th and 80th segment the azimuth changes randomly to assure equal sampling in all directions. The grain of the data is the segment length that has no further resolution. This means that, if more than one landscape element share a segment place, the exact position of the features within the segment cannot be determined in more detail. In order to ascertain the critical number of paths that are required for a statistically adequate representation of all land use types considered, the 9 km² study plot was sampled with an increasing number of random paths (minimum: 10; maximum: 100).

Results

Land use statistics without spatial resolution

The spatio-temporal data model that was employed enables the user to quickly generate land use statistics for any given perimeter and time step (Table 1). This is a necessary first step to obtain a general insight into the most decisive land use changes. For the illustrated area on the Swiss Plateau the percentage of openland is relatively constant over time. Unfortunately the topographic maps that were consulted do not allow for subdividing this habitat class into more detailed land use types, except for the element "orchards". This habitat type was monitored routinely since 1955, and is considered a very important feature for the avifauna of an area (Pauritsch and Harbodt, 1988; Weitnauer and Bruderer, 1987). Drastic decreases can be identified between 1955 and 1982 caused by intensified agricultural land use and an agricultural policy of the 1950's and 1960's which favored clear-cutting of tall fruit trees and the substitution with short growing plants.

The land use types that are mostly responsible for the partitioning of the landscape are wetlands, forests, residential areas, industrial complexes and transportation. The most apparent changes occur between the map editions of 1932 and 1942, and are due to the agricultural self-sufficiency program of the government during World War II. Extensively used land such as wetlands or fens were drained and reclaimed, which led to a lowering of the water table. Vast parts of the open canopy forest disappeared, causing a decrease in the forested area. Drastic increases are noted for the landscape elements roads, residential areas, and industrial complexes.

Disturbance maps

The general statistics described above do not reveal information on spatial changes, fragmentation or neighborhood relations of certain landscape elements, or on network characteristics of the landscape. In order to fill this disparity spatial analysis

Table 1. Land use over time on the study plot Inwil as generated with the spatio-temporal data model. All values are expressed in thousandths of the total area.

Year	Total area (km ²)	Open land (‰)	Subdivided into Orchards since 1955 (‰)	Residential areas, industries, transportation (‰)	Rivers (‰)	Wetlands (‰)	Hedges (‰)	Total forested area (‰)	Closed canopy forest (‰)	Open canopy forest (‰)	Wet closed canopy forest (‰)	Wet open canopy forest (‰)
1888	9.0	742	0	25	52	63	1	117	69	2	0	46
1898	9.0	743	0	27	52	61	3	114	64	7	0	43
1902	9.0	743	0	27	52	61	3	114	64	7	0	43
1909	9.0	743	0	28	52	60	3	114	64	7	0	43
1913	9.0	741	0	30	52	60	3	114	64	7	0	43
1932	9.0	761	0	34	48	33	4	120	66	13	2	39
1942	9.0	843	0	36	43	0	3	75	65	10	0	0
1955	9.0	851	203	42	45	0	3	59	58	1	0	0
1966	9.0	843	191	50	46	0	4	57	57	0	0	0
1971	9.0	833	158	53	46	0	6	62	62	0	0	0
1976	9.0	825	82	58	46	0	6	65	65	0	0	0
1982	9.0	819	78	65	44	0	6	66	65	1	0	0

of the data have been performed. In a first step, disturbance patterns have been analyzed to find landscape parcels that experienced similar impacts. Each land use type was assigned a quality rating between 1 and 4 to express whether it has an important nature protection function and represents a natural or traditionally managed land use type (value 1), or whether it is heavily disturbed and of no value for nature protection (value 4). The rating displayed in Table 2 is the result of an expert questionnaire and simply expresses an overall disturbance tendency of the corresponding land use type. It is clear that current paradigms of nature protection as well as the special research field of the experts are governing this quality rating (see also paragraph "discussion and conclusions"). However with the only exception of the landscape element "gravel pits", the expert opinions do not differ from each other by more than 1 score on the rank scale. The non-homogeneous scoring of gravel pits is due to the fact that this landscape element often hosts important amphibian populations. Thus, it received high nature protection scores from the zoologists but low scores from the geographers. The score which was used for the present analyses (i.e. value 4) represents a landscape ecologists' view on a broader scale. It assumes that gravel exploita-

tion is accompanied by vast disturbances of both the biological and geological resources in a given area.

The spatio-temporal data model allows quick calculation of degrading or upgrading tendencies over many map updates. To do so all differences of the quality rating between consecutive time steps are summarized for each spatial object according to formula 5 (see Appendix). Finally, land parcels that experience similar disturbances can be identified and displayed graphically. As an example, Figure 4 exhibits degrading tendencies within the study plot for two major periods, i.e. map editions between 1888 and 1942 (7 updates) and map editions between 1955 and 1982 (5 updates). For *plotting reasons* the vectorized map was generalized using a 20×20 m grid. If a cell is occupied by more than one land use parcel, the parcel with the highest absolute degrading value determines the final cell value. The minimum area of a land use parcel to be considered is 40 m^2 . This restriction prevents small sliver polygons that result from overlaying operations from generating artificial disturbance values that do not correspond with real land use changes. If a cell is occupied by land parcels with the same disturbance value, the biggest patch determines the final cell value. The two disturbance patterns exhibited in

Table 2. Expert quality rating of various land use types. Three experts were asked to rank the land use types from 1 (important nature protection function and/or traditionally managed land) to 4 (heavily disturbed; no value for nature or landscape protection).

Land use type	Quality rating used in this study	Range of quality rating (3 experts)
foot paths	1	1–2
small gravel roads < 2.5 m	2	2
paved roads 2.5–7 m	3	2–3
main roads > 7 m, freeways	4	4
railway tracks	3	2–3
residential areas	3	3
industrial complexes	4	3–4
small streams < 3 m	2	1–2
rivers > 3 m	2	1–2
hedgerows	1	1–2
orchards	2	2
openland	2	2–3
wetlands, alluvial plains	1	1
gravel pits	4	1–4
closed canopy forest	2	2
open canopy forest	1	1
wet closed canopy forest	1	1
wet open canopy forest	1	1

Figure 4 differ significantly. In the pre-World War II period (7 time steps), patch disturbance dominates over linear disturbance, whereas in the post-World War II period (5 time steps) main disturbances occur along lines. A common characteristic of both periods is the emergence of urban and industrial areas near Inwil, Root and Perlen respectively.

Fractals and patches

Fractals and information theoretic indices are useful tools to assess landscape patterns and changes in landscape structures (O'Neill *et al.*, 1988, 1992; Pastor and Broschart, 1990; Tarboton *et al.*, 1988; Turner, 1990). For our purposes, the fractal dimension, an area-perimeter ratio, was calculated for selected land use patches in five map editions i.e. 1888, 1932, 1942, 1955, and 1982. Habitat patches

that were considered are openland, wetlands, open/closed canopy forests and wet open/closed canopy forests. High values of the fractal dimension indicate a landscape that is composed of many patches with complex and convoluted shapes, whereas low values are typical for plane filling, simple geometric patches. As shown in Table 3, the fractal dimension (*d*) is slightly declining between 1888 and 1982, indicating a more geometric landscape in recent times. However the differences are small and it seems that this indicator is rather insensitive to human-induced landscape changes that are visible on topographic maps in the scale of 1:25'000. The other indices (number of patches and patch size), that are represented in Table 3, are good indicators for fragmentation processes. Land reallocation as well as drainage of wetlands during World War II caused patch aggregation which is expressed by significantly less but larger patches in 1942 than in 1888. This process is reversed in the post-World War II period with significantly smaller but more numerous patches between time step 1955 and 1982. The patchiness of the landscape in 1982 is similar to the pre-World War II period but the landscape patterns are more geometric and monotone.

Information theoretic indices

Information theoretic indices have been used to characterize the landscape patterns of the various time steps considered. The indices are strongly influenced by the total number of land use classes on a given landscape. Thus, in order to ensure comparable results for all time steps considered, the total number of landscape elements was limited to 9 classes, some consisting of various landscape elements that are grouped together. The diversity index (formula 1, Appendix) expresses the degree to which a given number of landscape elements are represented on a map in equal proportions. The higher the index the more diverse the landscape. Maximum diversity (formula 2, Appendix) is reached when all land use types are represented in equal proportions. The dominance index (formula 3, Appendix) is a measure to express to which

years 1888 - 1942 (7 time steps)

years 1955 - 1982 (5 time steps)

Intensity of disturbance

- No degrading tendency (DU = 0, see formula 5, Appendix)
- Medium degradation (DU = 1, see formula 5, Appendix)
- High degradation (DU = 2, see formula 5, Appendix)

Fig. 4. Disturbance maps of the study plot for two time periods, i.e. 1888–1942 and 1955–1982. Degrading or upgrading tendency of each 20×20 m pixel was calculated using formula 5 (Appendix). For plotting reasons the graph exhibits degrading trends only.

degree certain land use types dominate the landscape. For our purpose the index was normalized to range from 0 to 1. High values indicate that one or only a few habitats are dominating the scene, low values suggest a landscape that has many land uses represented in approximately equal proportions.

Table 4 provides evidence of the overall tendency of the two indices over time. It appears that the big landscape disturbances that took place during World War II caused considerable changes in the values. After approximately 30 yrs the trend is being reversed and both indices converge towards a

Table 3. Fractal dimension and patchiness of selected habitat types in five consecutive time steps as calculated from vectorized land use data. The landscape elements considered are openland, wetlands, open/closed canopy forests, and wet open/closed canopy forests.

Year	No. of patches	Patch size, percentiles (ha)			Comparison of patch size between two consecutive time steps ¹		Fractal dimension (d)
		25th %	50th % (median)	75th %	t-test unpaired	Mann-Whitney	
1888	226	0.06	0.65	3.54			1.94
1932	221	0.04	0.44	3.48		***	1.90
1942	141	0.14	1.10	4.17	*	**	1.88
1955	157	0.17	0.82	3.86			1.88
1982	244	0.09	0.47	2.08	*	**	1.84

¹2-tail probability: *(0.051–0.100), ** (0.011–0.050), *** (< 0.010)

pre-World War II level. However the landscape elements that cause high diversity and low dominance in the pre-World War II period are not identical with those of the 1970's and 1980's. Moreover it is the fast growing group of ecologically low rated elements like traffic, residential areas and industrial complexes that cause the indices to reach the level of the 1930's.

Edge analysis

Edges play an important ecological role as transition zones between different habitats (Forman and Godron, 1986; Haila, 1986; Helle and Helle, 1982). The ecological resources or life requisites in these zones are often utilized by significantly more species than in the interior of adjacent habitats, and species diversity is often higher. Positive effects of edges on biodiversity could be shown for forest-openland edges as well as for hedgerows (ANL, 1982; Vickholm, 1983). The present landscape historic data allow classification and assessment of edges over time. Edge length between different habitats was calculated using a program of Turner (1990). The edge calculation requires rastered data which were generated using routine procedures of the GIS software ARC/INFO. The cell size is assumed to be 20 × 20 m. This reduction in the resolution of the data set causes the fractal dimension (see Table 3) to be lowered by approx. 10% in all time steps considered. Each cell in the grid is assigned a code according to the polygon (land use

type) it overlays. If a cell has more than one possible code (i.e. contains two or more land use types) the code of the polygon with the greatest area in the cell is used. Following this rule, linear elements such as rivers or hedgerows may completely disappear from the grid. This can be avoided by assigning a higher priority to linear elements which ultimately take precedence over other features if they share a grid cell. In the resulting landscape pattern, linear elements are generally overestimated and are represented with a buffer of approximately 15 m on each side of the initial width of the element. This buffer band can be interpreted as the transition or edge zone to neighboring elements, where ecological characteristics of both land use types are present. On the generalized grid map the land use categories were grouped as follows:

- openland
- residential areas, industrial complexes, transportation
- rivers
- hedgerows
- wetlands
- closed canopy forest
- open canopy forest
- wet closed canopy forest
- wet open canopy forest

The edge types were grouped according to ecological quality and increasing, stable, or decreasing length between 1888 and 1982 (Figure 5). The quality rating is the result of an expert questionnaire. Out of 36 possible edge combinations (9 land use

Fig. 5. Length of various edge types in five consecutive time steps as calculated from 20×20 m grid data of the study area Inwil. The edge types are grouped according to ecological quality and increasing, stable, or decreasing trend between 1888 and 1982. For the description of the groups see text.

Table 4. Information theoretic indices for the study plot Inwil in five consecutive time steps.

Year	Diversity (H)	Max. diversity (Hmax)	Dominance (D)
1888	0.986	2.197	0.551
1932	0.978	2.197	0.555
1942	0.640	2.197	0.709
1955	0.603	2.197	0.726
1982	0.694	2.197	0.684

classes) only 15 have quantitative importance for the present landscape and account for more than 99% of the total edge length in all time steps considered. It is obvious from Figure 5 that the length of edge types with a low ecological value (group 5) increases gradually between 1888 and 1982. On the other hand many ecologically important features show decreasing trends (groups 2 and 3). However, the transition zones between hedgerows and other habitats (group 1) seem to increase slightly over the entire time period. It is remarkable that in all time steps considered, edge types of high ecological quality do not account for more than 20% of the total edge length. This in turn makes them very vul-

nerable to disturbances such as the removal of ecologically high-rated habitat patches. This effect can be best illustrated with the removal of approximately 0.75 km^2 of wetlands and open canopy forests between 1932 to 1942 (approximately 7.5% of the total area of the study plot). Due to this disturbance a total of 5 edge types with medium to high ecological value were eliminated. This corresponds to a 30% decrease of all 15 edge types considered and a 40% reduction of the ecologically important edge types (11 medium to high quality types). This trend towards a more simple and less diverse edge system can also be illustrated in Table 5 featuring the relative contribution of each edge type to the total edge

Table 5. Relative contribution of different edge types to the total edge length within the study plot Inwil (raster data, 20 × 20 m grid).

Ecological quality of edge	Relative edge length (% of total edge length) year of survey				
	1888	1932	1942	1955	1982
low	47.2	38.7	45.0	54.5	61.1
medium	38.5	38.6	42.0	34.8	24.9
high	13.6	20.3	12.7	10.7	13.9
unclassified	0.7	2.7	0.4	0.5	1.2
total edge length (km)	179.4	176.8	157.2	167.9	192.8

Table 6. Traverse analysis: Correlation between the relative frequency of occurrence (counts) of 17 landscape elements and the relative area of the corresponding landscape elements. The analysis was performed for the 1888 map edition of the study plot Inwil. Two sampling methods (i.e. random vs. systematic) were employed to conduct the counting.

Sampling method	Number of traverses	Number of 25 m segments within investigation area	Total number of landscape elements crossed (counts)	Correlation coefficient (Spearman)
random traverses 100		3030	8869	.946
random traverses 90		2885	7911	.949
random traverses 80		2535	7039	.941
random traverses 70		1937	6379	.944
random traverses 60		1863	5548	.944
random traverses 50		1704	4620	.942
random traverses 40		1380	3980	.942
random traverses 30		1157	3016	.938
random traverses 20		905	1928	.904
random traverses 10		399	1113	.676
systematic grid 24		2620	3296	.959
systematic grid 13		1440	1815	.953
systematic grid 7		760	745	.867
systematic grid 4		420	517	.924

Critical correlation coefficient for 99% significance level: 0.618 (Gibbons, 1985)

length. It is obvious that in 1932 the edge length of ecologically important edge types was at its highest level: Sixty percent (60%) of the total edge length was of medium to high ecological value. In 1982, on the other hand, the percentage of ecologically important edges dropped to about 40% of the total edge length. However some high quality edges (i.e. hedgerows vs. openland and rivers, Figure 5) show a consistent increase since 1888 due to several planting efforts (i.e. windbreakers and hedgerows along channeled rivers and freeways).

Traverse analyses

Traverse analyses were performed to assess spatial relationships between habitats of different ecological value or degradation in different periods of the land evolution process (Figure 3). The screening allows inferences about the development of the habitat/barrier frequencies over time. Prior to the analyses the critical number of random or systematic transects that gave a statistically representative count of all land use types considered was determined. To do so the counts of landscape elements that are crossed in an increasing number of random traverses (10 to 100) or systematic traverses (4–24)

were compared with the relative area of the corresponding land use types using the non-parametric rank correlation coefficient procedure of Spearman (Feldman *et al.*, 1987; Hollander and Wolfe, 1973). On the 99% significance level a minimum of 10 random traverses are required to ensure an adequate representation of all landscape elements (Table 6).

The comparison between sampling along random traverses and sampling along a regular grid shows two main results (Table 6): Firstly, for an identical number of segments the number of landscape elements that are crossed with systematic sampling along regular grid lines is significantly lower than with random sampling. For the area considered the ratio is 2:1. It is most likely that the overall north-south and east-west orientation of many linear landscape elements in the study plot reduces the number of crossings in a regular north-south/east-west grid. The effect may be reduced with a rotating systematic grid. Secondly, despite the lower number of counts, systematic sampling requires fewer segments than random sampling to ensure an equally valid estimate of the landscape pattern. These findings are confirmed in Zöhrer (1980). However, since a rotating systematic grid with adequate representation of all azimuths would consume a similar amount of computing time, and the sampling did not have to be conducted in the field, we preferred random sampling. In order to ensure a statistically sound data set, a total of 100 random traverses with over 3000 segments was used for the analysis of the spatial relationships between habitat types.

According to an expert questionnaire the monitored landscape elements were divided into landscape elements of high and medium ecological quality (referred to as "habitats") as well as into landscape elements of low ecological quality (referred to as "barriers"):

- *landscape elements of high and medium ecological quality ("habitats")*: openland, hedgerows, rivers, wetlands, open/closed canopy forest, wet open/closed canopy forest, orchards
- *landscape elements of low ecological value ("barriers")*: roads > 3 m width, freeways, railway tracks, residential areas, gravel pits, industrial complexes

Traverse analysis revealed important insights into the development of landscape fragmentation over time. The following key variables were calculated routinely for each habitat type and time step:

- total number and area of "habitat patches" along the traverse;
- distance between the inner borders of two neighboring patches of the same habitat type (in between these two patches other landscape elements might be located);
- total number of neighboring habitat patches that are separated by one or more barrier elements;
- total number of neighboring habitat patches that are *not* separated by one or more barrier elements;
- distance between habitat edges and its closest barriers.

The entire procedure is repeated for each habitat type. The ecological correlary would be the study of the movement of larger animals in a patchy landscape. Figure 6 exhibits habitat/barrier frequencies over time for selected habitat types. For all high to medium quality patches (Figure 6a), the total number of patches increases by more than 50% between 1888 and 1982 despite a slight decrease in the total area of the corresponding patches. The increase is most pronounced in the post-1950 period. This fragmentation process results in an increasing number of habitat pairs that are separated by low quality features, and a decrease of the number of habitat pairs without any barriers in between. Many of these changes are significant with a two-tail probability of 5% (Friedman test, Feldman *et al.*, 1987; Hollander and Wolfe, 1973). As a general result we might conclude that the barrier effect was least pronounced in the 1932 map edition with a maximum of non-separated habitat pairs, and it was highest in the 1982 landscape pattern. The 1888 pattern is located somewhere between the 1982 and the 1942 situation. These trends are even more pronounced for forest patches (Figure 6b). A general decreasing tendency of the forested area between 1932 and 1955 is followed by a slight increase in the post-World War II period. However, despite the 50% decrease in forested area between 1932 and 1955, fragmentation and barrier effects are increas-

Fig. 6. Habitat/barrier analysis by means of sampling along random traverses (100 traverses à 2.5 km; segment length 25 m). Each graph displays the temporal development of the following four key variables:

- ① total area of habitat patches (—)
- ② total number of habitat patches (---)
- ③ total number of neighboring habitat pairs (i.e. forest–forest; openland–openland) that are separated by a barrier (.....)
- ④ total number of neighboring habitat pairs (i.e. forest–forest; openland–openland) that are *not* separated by a barrier (— · — · —).

ing in the post-World War II phase and are highest in the 1982 map edition, indicating a general intensification of forest management in this region.

The fragmentation process in a landscape can also be demonstrated with the distance between habitat patches and nearest barriers (Figure 7). If all medium and high quality habitats are considered (Figure 7a), the 1932 map edition seems to exhibit the least fragmented landscape with greatest distances between habitats and first barriers. Subsequently, the values decrease to reach an absolute minimum in 1982, indicating a general loss of buffer area around habitat patches. It is obvious that the fragmentation process excessively diminished long, undisturbed corridors between habitat patches as suggested by the rapid decrease of the 76th to 90th percentile in the post-1930 period. For forests (Figure 7b) this process might be an extremely decisive factor governing species movement. While in 1932 when 40% of all barriers were more than 250 m distance from the previous forest edge along the transect, this number decreases to only 14% in 1982.

Fig. 7. Distances between habitat patches and nearest barriers as calculated by means of sampling along random traverses. The graphs show the 50th, the 75th, and the 90th percentile of the distances between habitat edge and the first low-quality feature (barrier) along the traverse (i.e. forest edge–road; hedgerow–road).

Discussion and conclusions

At the present stage of our knowledge, there seems to be a general consensus about the importance of landscape historical analysis in the landscape evaluation process (Pedroli and Borger, 1990; Williams, 1989). However, for many practically working agencies that are designing nature management plans, access to historic land use data is hindered by a lack of powerful documentation techniques. With the technical development of Geographical Information Systems (GIS) this deficiency might be corrected in the near future. Nevertheless, the temporal component of spatial data is often neglected in commercial implementations and a special effort is generally needed to adapt the currently available systems to the requirements of a modern landscape historical database. The spatio-temporal data model presented in this paper is a ready-to-use approach for any commercial GIS and can be used for landscape historical databases as well as for routinely updated inventories of biotope resources. Each time step can be accessed from any point in space or time. This in turn enables the user to eval-

uate a landscape patch not only by its present land resources but also according to its historical evolution. Thus, the data structure is a departure from the conventional approach of analyzing analog maps for each time step with only very limited access to the temporal component. As a consequence of this study a majority of the biotope inventories of the Swiss Environmental Protection Agency are updated using the proposed methodology. Despite the potential of the procedure we should be well aware of the limits of electronically stored and updated maps. As shown extensively by Johnson (1990), numerous error sources originating from digitized maps, data processing, overlays etc. might cause inaccurate results, which, at least for the practitioner, could cause unwanted legal problems associated with cadastral plans. In the data set presented, locational errors are the most serious inaccuracies. They are caused by numerous sources such as, a) inaccurate location of landscape elements in the historical maps, b) numerous editing processes and c) overlay algorithms. In order to eliminate, control, or assess these error sources various control mechanisms had to be introduced. A good example of such a control mechanism is the automated elimination of artificial land use changes occurring as small sliver polygons during overlay operations (see paragraph "Disturbance maps" for more details). Another example is the cross-dating and cross-check of the topographic sheets with independent data from aerial photographs or other historical records.

Despite the strict quality control topographic sheets are only a sketch of real patterns and processes, and the ecological value of the elements depicted is often difficult to assess. Only larger structures of the landscape can be investigated and impacts on a finer ecological scale such as chemical input, fertilization, or air pollutants are impossible to estimate. The category "openland" for example is a very heterogeneous class and can hardly be subdivided into groups of different land use intensity. Consequently any rating into classes of different ecological quality as demonstrated in this paper has to be interpreted with caution. The rating only expresses an overall disturbance tendency of the corresponding landscape element and is, in this paper, considered

a conservative estimate. Openland parcels, for example, were assigned a medium rating to express the ecological quality over the entire time period from 1888 to 1982 although during the period of intensive agricultural land use (1960 to present), fertilization, pesticides etc. have drastically diminished the ecological quality of the soils. Despite the limits of such an expert rating, the land use matrix presented in this paper allows the user to quickly assess most important areas with degrading or upgrading disturbance tendencies. In combination with edge analysis, calculation of information theoretic indices and traverse analysis, changes in the ecological sustainability of the study plot can be identified in a rather detailed form.

In contrast to findings of Turner and Ruscher (1988) the information theoretic indices diversity and dominance show clear variation with time. The most pronounced event that causes great changes in the indices is the World War II disturbance with the removal of wetlands to increase agricultural and wood production. It takes more than 30 yrs until the disturbance is no longer visible in the indices.

The most powerful tool of the methods evaluated in this paper seems to be traverse analyses. They enable the user to assess spatial relationships between habitat patches and barriers. Although comparable with a species movement in a patchy landscape (Storms *et al.*, 1976), it is merely an estimate of the free way length between patches. Concerning the design of such traverses it was shown that a random approach is an effective sampling method. In the present analysis we used the random approach despite the higher number of samples that are required to obtain an equally valid estimate than systematic sampling. Since the sampling was not conducted in the field, the higher number of samples was not a decisive economic factor. Within the study plot the average barrier frequency between selected habitat types increases drastically in the last 100 yrs with a minimum in the 1930's. As a result, the distance between barriers and habitats diminishes considerably which translates into a significant reduction of the undisturbed transition zone between high and low quality features.

On the basis of all landscape indices calculated,

landscape structures on the plot investigated seem to be ecologically most sustainable in the 1930's, with a high diversity of edge types and a significantly lower frequency of barrier elements compared with the post-World War II and the pre-World War I period. There is no indication to consider landscape structures of the past century as ecologically superior to the 1930's and 1940's of this century, but there is clear evidence that most indices exhibit a significant degradation in the post-World War II period that goes beyond the conditions of the last century. Degradation continues until the 1970's due to an intensive agricultural and industrial land use. The 1950's can be classified as the structurally poorest period of all time steps analyzed. Since the 1970's an upgrading tendency can be observed. This is a clear sign that conservation efforts of the post-1970 period are now becoming visible even in maps of the 1:25'000 scale. Thus, the present study appears to be an ideal monitoring system to evaluate success or failure of landscape and nature conservation laws over larger areas.

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Appendix

Diversity (H)

$$H = - \sum_{k=1}^m (P_k) \ln(P_k) \quad (1)$$

where

m = number of land use types observed on the map

P_k = relative area of land use type k (100% = entire study area)

Maximum diversity (H_{max})

$$H_{max} = \ln(m) \quad (2)$$

where

m = number of land use types observed on the map

Dominance, normalized (D)

$$D = \frac{(H_{max} - H)}{H_{max}} \quad (3)$$

Fractal dimension (d)

$$S \sim 0.25P^d \quad \text{or} \quad \ln S \sim d \ln \frac{P}{4} \quad (4)$$

where

S = area of a patch

P = perimeter of a patch

d = fractal dimension

Degrading or upgrading tendency of a spatial object (DU)

$$DU = \sum_{i=1}^n (a_{i+1} - a_i) \quad (5)$$

where

a_i = quality rating in time step i

n = number of time steps in land use matrix