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Research

Time Series of Landscape Fragmentation Caused by Transportation Infrastructure and Urban Development: a Case Study from Baden-Württemberg, Germany

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ABSTRACT. Landscape fragmentation is increasingly considered an important environmental indicator in the fields of sustainable land use and biodiversity. To set goals for future development and to plan appropriate measures, suitable empirical data on the degree of landscape fragmentation are needed to identify trends and compare different regions. However, there is still a significant lack of data on landscape fragmentation as an indicator, despite the substantial scientific literature on this topic, likely because of confusion over the definition of "fragmentation," questions associated with scale and data issues, and lack of general agreement on a fragmentation measure. This study presents a state-wide quantitative analysis of landscape fragmentation in Baden-Württemberg, Germany, by means of the "effective mesh size" (m_{eff}), which characterizes the anthropogenic penetration of landscapes from a geometric point of view and is based on the probability that two randomly chosen points in a landscape are connected, i.e., not separated by barriers such as roads, railroads, or urban areas. Baden-Württemberg is fragmented to a far greater extent than indicated by previous studies. The m_{eff} has decreased by 40% since 1930. This development is strongly related to the growing number of inhabitants, the increased use of motorized vehicles, and the hierarchical regional planning system based on the central place theory. To illustrate the suitability of the m_{eff} method for environmental monitoring, as a planning instrument and as an assessment instrument for impact assessment studies, we explored several variations of applying the method with regard to choice of fragmenting elements, consideration of noise bands, spatial differentiation (e.g., administrative districts vs. ecoregions), and way of dealing with patches at the boundaries of the reporting units. Depending on the objectives of the investigation (e.g., recreational quality vs. suitability for wildlife habitat), different variations may be most appropriate. The insights and quantitative results from Baden-Württemberg provide a yardstick for analyzing and assessing landscape fragmentation in other countries.

Key Words: *effective mesh size; environmental indicators; landscape change; landscape fragmentation; landscape indices; monitoring; railroads; roads; sustainable development; time series; traffic; urban sprawl*

INTRODUCTION

Transportation infrastructure and urban development are two major drivers of landscape change worldwide (e.g., Meyer and Turner 1994, Forman et al. 2003, Bürgi et al. 2004). Landscape fragmentation caused by transportation infrastructure and urban development has a number of effects on almost all components of landscapes, including aesthetic, ecological, historical, and recreational qualities, e.g., tranquillity, scenery, and landscape character (Canters 1997, National Research Council 2002, Forman et al. 2003). Development of transportation infrastructure and urban areas further enhances the dispersion of pollutants and acoustic emissions and affects local climatic conditions, soil and land cover, water balance, and land use (e.g., Vitousek et al. 1997, Jaeger 2002).

Roads and railways act as barriers to movement for many animal species (Spellerberg 1998, Trombulak and Frissell 2000, Carr et al. 2002, Forman et al.

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2003). In combination with growing urban areas and intensified agricultural land use, they increasingly narrow and separate the remaining wildlife habitats (Forman 1995, Hammer et al. 2004, Robinson et al. 2004). This ongoing process of rapid anthropogenic landscape change is affecting numerous wildlife species, in particular species that require large areas (e.g., lynx *Lynx lynx*, red deer *Cervus elaphus*, otter *Lutra lutra*, Eurasian badger *Meles meles*, Eurasian capercaillie *Tetrao urogallus*, and Lesser Spotted Eagle *Aquila pomarina*), and is contributing to the endangerment and loss of biodiversity in many industrialized countries (van der Zee et al. 1992, Glitzner et al. 1999, van der Grift 1999, Underhill and Angold 2000, Marzluff 2001, Forman et al. 2003). Viable populations require minimum areas of habitat, smaller than which populations are prone to extinction (With and King 1999, Fahrig 2001, 2002). Therefore, the degree of landscape fragmentation is an essential indicator of the threat to species.

Despite the German Federal Government’s declared goal to “reverse the trend in land consumption and landscape fragmentation” (Bundesminister des Innern 1985), and despite the intention to preserve large, unfragmented spaces as a central principle of regional planning, landscape fragmentation in Germany has increased considerably over the past 20 years. In 1998, the German Study Commission on the Protection of Humans and the Environment stated that “evident urban sprawl is already leading to a noticeable loss of landscape quality for leisure, conservation, and in some cases, even for living” (Deutscher Bundestag 1998). However, this issue has so far not been treated as a high priority item on the political agenda.

There is a pressing need for comparative data on the current level and increase of landscape fragmentation as a robust quantitative basis for planning, future legislation, and development of a reliable indicator of landscape fragmentation (Kupfer 2006). For example, the report on “The State of the Nation’s Ecosystems—Measuring the Lands, Waters, and Living Resources of the United States,” which suggested 103 indicators, includes seven indicators of fragmentation (Heinz Center 2002, O’Malley et al. 2003, Kupfer 2006). However, data were available for only two of the seven fragmentation indicators, and those data were for a single point in time only, i.e., no trends.

Indicators of the state of the biophysical environment are a crucial instrument for linking environmental science with decision making, planning, and politics (Schupp 2005, Kupfer 2006). In addition to environmental monitoring, data on the degree of landscape fragmentation are relevant for environmental impact assessments on the level of projects, programs, plans, and policies. Depending on the specific purpose, different variants of applying measures of landscape fragmentation may be most suitable. Therefore, planners and other experts involved in environmental impact assessments need to understand the strengths and limitations of the various variants of applying landscape fragmentation measures in sufficient detail to make the right choices and avoid misuse (Li and Wu 2004). Such variants relate, among others, to the determination of relevant fragmenting landscape elements, consideration of disturbance zones, choice of reporting units, and the treatment of patches crossing the boundaries of reporting units.

A crucial question in the development of indicators of landscape fragmentation is which landscape elements should be considered as fragmenting elements. Some landscape elements may be complete barriers to animal movement, whereas others are filters of varying effectiveness. In addition to motorways and federal, state, and rural roads, many municipal roads in Germany have high traffic volumes (often more than 1000 vehicles per day) and, thus, act as significant barriers and sources of mortality for many species, e.g., amphibians (Hels and Buchwald 2001). However, former studies of landscape fragmentation have neglected to examine municipal roads (Bundesamt für Naturschutz (BfN) 1999, Schumacher and Walz 2000, Gawlak 2001). Therefore, we were interested in how much municipal roads contribute to the degree of landscape fragmentation.

Some road effects are restricted to the roadway itself, such as traffic-induced mortality, whereas others extend into the adjacent landscape, such as traffic noise affecting breeding birds (Reijnen et al. 1995a, 1995b, Forman et al. 2003). The distances over which the various road effects extend into the adjacent landscape depend on the characteristics of the road and the landscape, e.g., traffic volume (“road effect zone,” Forman and Deblinger 2000). Increasing width of the noise band created by road traffic indicates that the road becomes more and more impermeable for animals. A measure of landscape fragmentation that is based on the sizes of the remaining patches in the landscape can reflect this effect of increasing traffic volume when the sizes of the patches are reduced by the area of the noise band. Therefore, we asked how much noise bands influence the degree of landscape fragmentation.

In contrast to administrative districts, ecoregions are defined according to ecological criteria. However, monitoring reports on environmental sustainability often give indicator values only for administrative districts because they are considered more effective in political discussion. We were interested in what the differences were in the values of landscape fragmentation between these two categories of reporting units.

The boundaries of the reporting units often do not coincide with the fragmenting elements in the landscape. Therefore, patches crossing the boundaries of reporting units need to be attributed to the reporting units in some suitable way. We explored the question of what influence different attribution algorithms have on the resulting degree of landscape fragmentation.

We analyzed the historical development of landscape fragmentation in Baden-Württemberg, Germany since 1930. The state of Baden-Württemberg (35 751 km²) covers the southwestern part of Germany and borders Switzerland in the south and France in the west. The main geographical characteristics include various densely populated and heavily industrialized regions (such as Stuttgart, Heilbronn, and Mannheim), several regions of low mountain ranges (most importantly the Swabean Alb and the Black Forest), and many more or less intensively used agricultural landscapes. Baden-Württemberg's basic hydro-geographical components are Lake Constance, the Upper Rhine, the upper reach of the Danube, and nearly the entire basin of the Neckar river. A well developed and growing system of urban centers in connection with two major European transportation axes leads to relatively high degrees of landscape fragmentation in some parts of the state.

The objective of this paper is to present a case study that provides a yardstick for analyzing and assessing landscape fragmentation in environmental monitoring, and a means for developing quantitative goals for the future degree of landscape fragmentation, e.g., for application in environmental impact assessments. We pursue this objective by addressing the following research questions, based on a comparison of the degree of landscape fragmentation among the four principal administrative districts of Baden-Württemberg, the 44 rural districts, or counties, and the 66 ecoregions.

1. What is the degree of present-day fragmentation of these regions, and what is their ranking order?
2. How much has the degree of fragmentation of these regions changed during the last 70 years?
3. How much do the results differ when the municipal roads are included or excluded from the analysis?
4. How much do the results change when the increasing width of noise bands caused by higher traffic volumes is included in the analysis?
5. How much does the way that patches crossing the boundaries of reporting units are attributed to the reporting units influence the degree of fragmentation?

We related the quantitative results to the history of Baden-Württemberg, emphasizing the growth pattern of the human population and the increased use of motorized vehicles.

METHODS

The Fragmentation Measure "Effective Mesh Size" (m_{eff})

The scientific literature offers various methods for quantifying landscape fragmentation (e.g., Gustafson 1998, Hargis et al. 1998, Jaeger 2000, McAlpine and Eyre 2002, Rutledge and Miller 2006). Jaeger (2002) compared 22 metrics with regard to their reliability for quantifying landscape fragmentation, and systematically examined the eight most promising indices based on eight suitability criteria: intuitive interpretation, mathematical simplicity, modest data requirements, low sensitivity to small patches, monotonous reaction to different fragmentation phases (i.e., perforation, incision, dissection, dissipation, shrinkage, and attrition), detection of structural differences (e.g., the bundling of traffic lines), mathematical homogeneity, and additivity. According to these criteria, the effective mesh size (m_{eff}) was unreservedly appropriate as a fragmentation measure, whereas the suitability of the other measures was more or less severely limited (see also Jaeger (2000) for a condensed version). For example, average patch size and the density of roads and railways do not provide any information on the distribution of the barriers in the landscape (e.g., bundled or spread out evenly) and, thus, hardly give an indication of the size of the remaining patches, which can vary greatly, depending on the patterning of the routes. Measures of variance in patch size and moving-window analyses would also give information about the relative density of roads across a landscape, but they are less straightforward to interpret than the m_{eff} (see below) and would also need to be tested based on the eight suitability criteria.

The method chosen here is based on measuring the m_{eff} (Jaeger 2000), which can be easily obtained and interpreted. The method has several advantages over most other approaches (Jaeger 2000).

- This method includes all the patches remaining in the network of transportation infrastructure and urban zones, according to their size.
- It affords a comparative assessment of different landscapes and provides a simple way of showing trends (illustrated in time series).
- The reliability of the method has been checked on the basis of eight suitability criteria through a systematic comparison with other quantitative measures (see above).
- The method can be extended to include the permeability of roads for animals or humans moving in the landscape (i.e., filter effect) and the relative location of the patches (Jaeger 2002).

The m_{eff} is suitable for comparing regions with differing total area and with differing portions occupied by housing, industry, and transportation structures.

The basic idea of m_{eff} is that it expresses the probability that any two randomly chosen points in the region under observation may be connected, i.e., not separated by barriers such as roads, railroads, or urban areas (Fig. 1; Jaeger 2000, 2002). It can also be interpreted as the possibility that two animals of the same species—placed randomly in a region—will find each other. The more barriers in the landscape, the lower the probability that the two points will be connected, and the lower the m_{eff}.

The connection probability is given by

$$C = \sum_{i=1}^{n} \left(\frac{A_i}{A_t} \right)^2 \quad (1)$$

and the effective mesh size is

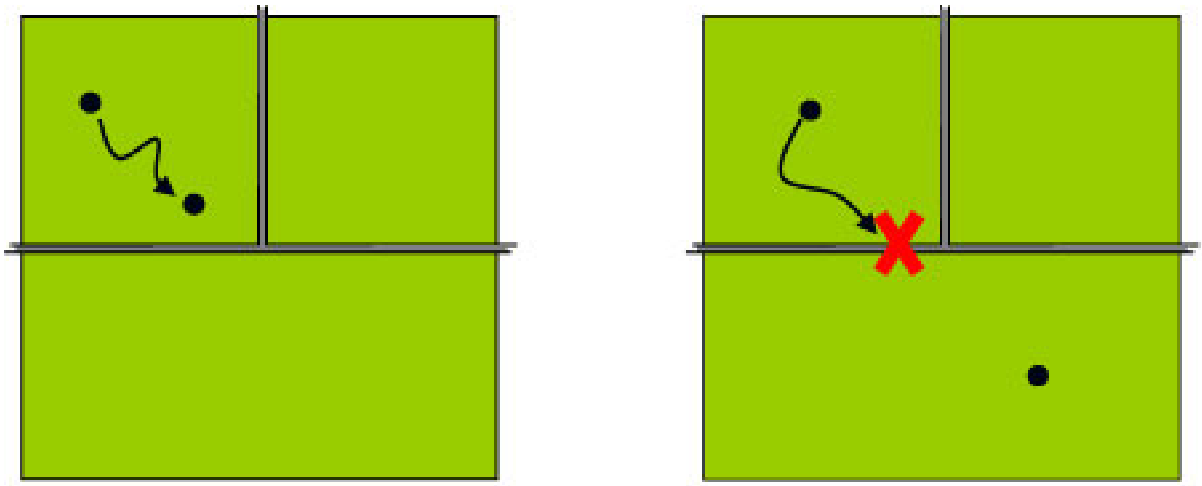
$$m_{\mathrm{eff}} = A_t \cdot C = \frac{1}{A_t} \sum_{i=1}^{n} A_i^2 \quad (2)$$

where n = the number of patches (excluding urban development), A_i = size of patch i, and A_t = the total area of the region under investigation.

This definition is supported by several features:

1. *Simplicity*: the connection probability of any two points is the simplest approach for determining fragmentation in terms of a probability; more points are not required, whereas single points are insufficient.
2. *Transparency*: the definition is transparent and makes intuitive sense, because the probability of two points being connected can be directly expressed in a mathematical formula. The probability that a randomly chosen point is in patch 1 is:

Fig. 1. Two randomly chosen points are connected when there is no barrier between them.



$$\frac{A_1}{A_t} \quad (3)$$

So is the probability that the second point is in A_1. The probability that both points are in patch 1 thus is:

$$\left(\frac{A_1}{A_t}\right)^2 \quad (4)$$

The probabilities for all the patches 1 to n are added up:

$$\left(\frac{A_1}{A_t}\right)^2 + \left(\frac{A_2}{A_t}\right)^2 + \left(\frac{A_3}{A_t}\right)^2 + \ldots + \left(\frac{A_n}{A_t}\right)^2 = \sum_{i=1}^{n} \left(\frac{A_i}{A_t}\right)^2 = C \quad (5)$$

To make this quantity comparable to other regions with different total areas, it is re-calculated in terms of the size of a patch: the m_{eff}. This is deduced through multiplication with A_t, which leads to the above formula for the m_{eff}, because

$$A_t \cdot \sum_i \left(\frac{A_i}{A_t}\right)^2 = \frac{1}{A_t} \cdot \sum_i A_i^2 \quad (6)$$

3. *Intuitive interpretation as a condition of persistence*: the m_{eff} can be directly interpreted as a factor influencing the persistence of populations, as the probability of two animals meeting each other is the prerequisite for reproduction and thus for the persistence of a species in a region (as well as for genetic exchange in a metapopulation).

4. *Mathematical properties*: the m_{eff} has highly advantageous mathematical properties. For instance, it is relatively unaffected by the inclusion or exclusion of small and very small patches, and owing to its mathematical properties, the measure is suitable for comparing regions of differing total sizes.

5. *Consideration of the structure of the transportation and settlement network*: in contrast to the density of roads and railroads, the m_{eff} expresses changes in the spatial patterning of transportation lines (e.g., bundling of traffic lines).

> The maximum value of the m_{eff} is reached with a completely unfragmented landscape: the m_{eff} then equals the size of the whole landscape. If a landscape is divided up into patches of equal size, then the m_{eff} equals the size of these patches. However, it is not usually equal to the average size of the patches. The minimum value of the m_{eff} is 0 km² when a region is completely covered by transportation and urban structures.

Application of the m_{eff} method implies a decision about which landscape elements are considered relevant for fragmentation (e.g., transportation infrastructure and urban development) and the definition of reporting units (e.g., states, rural districts, ecoregions) in which the degree of fragmentation is to be determined (Gulinck and Wagendorp 2002). Various geographical data layers, e.g., the roads, railways, and urban areas layers, have to be combined to determine the patches belonging to a reporting unit. Several approaches are possible for this (see also Moser et al. 2007, Jaeger et al. 2007):

1. All patches sharing at least some of their area with the reporting unit are considered to be part of the reporting unit.
2. All patches that are entirely within the boundaries of the reporting unit are considered to be part of the reporting unit.
3. *Central-point procedure*: all patches whose center (centroid) lies in the reporting unit are considered part of the reporting unit.
4. *Cutting-out procedure*: the patches are cut out by the boundaries of the reporting unit, i.e., the border of the reporting unit serves as an additional boundary for the patches close to the border. The patches within the border of the reporting unit will be included in the analysis. This tends to cause the m_{eff} to be underestimated because the edge patches often appear smaller than they are in reality.

The first two methods were rejected because, with method 1, those patches crossing the boundaries of a test area are considered part of several reporting units at the same time, whereas with method 2, these patches are not consigned to any reporting unit. The cutting-out (CUT) and central-point (CTRP) procedures both provide a clear and complete allocation of the patches to the reporting units. Despite the tendency for edge patches to be regarded as being smaller than they really are, the fact that the reporting unit needs definite borders for establishing a time series argues in favor of the CUT procedure. The CTRP procedure, however, allows for changes occurring in the outer boundary of the actual area under observation (e.g., caused by new roads near the boundary). Both methods may be implemented, depending on the problem addressed. For analyzing the influence of an area's boundaries on its degree of fragmentation, we applied both methods and compared the results. Because of the large amount of quantitative results, we present just one example in this paper (see the "District Level" section below; full results for the years 1998 and earlier can be found in the technical report by Esswein et al. 2002). In most cases, we show the results of the CUT procedure.

Data Used for Analysis

This study is the first to quantitatively investigate the development of landscape fragmentation in a German state over a time span of seven decades. We used topographic maps of Baden-Württemberg at a scale of 1:200 000. The analysis was conducted for the year 2004 and for five time steps in the past (1998, 1989, 1977, 1966, 1930). We used digital ATKIS data for the years 1998 and 2004. The maps for the years 1989 and earlier were geo-referenced, then the roads, railways, and settlements were digitized "backward" starting with the ATKIS data of 1998 (for technical details see Esswein et al. 2002).

Landscape elements we considered as impediments to animal movement or to people seeking recreation, and as sources of emissions, were federal motorways and federal, state, rural, and municipal roads, railways, urban development, and industrial areas (urban zones). We also included the natural fragmentation caused by rivers (from 6 m in width) and lakes because they are also relevant barriers for the many species that cannot cross them and whose access to resources on the other side of a lake may be restricted by a road that leads to the lake shore or riverbank.

The digitized processing is based on the geographical data from the "Spatial Information and Planning System" (RIPS) (Müller 2000). We used the ArcInfo® geographical information system (Environmental Systems Research Institute (ESRI) 2002) to create the patch geometry from the various topic layers. The roads were represented by vector data having zero width. We omitted roads that were joined to the network at only one intersection (i.e., incisions), because they do not entirely dissect patches and their traffic density is usually extremely low. Those parts of the resulting mosaic that were not settlements or lakes are the patches that were used to calculate the m_{eff}.

The data from Baden-Württemberg illustrate a comparison of different parts of a state. In addition to a state-wide overview, we conducted three analyses based on the four main administrative regions, the 44 rural districts, and the 66 ecoregions in Baden-Württemberg. Bearing in mind the varying sensitivity of landscapes to fragmentation, we consider areas with high biotope density as examples of areas with high sensitivity to fragmentation (see the last section of the Results).

Traffic Volumes and Noise Bands

Traffic volume has increased considerably since 1930. Noise is one of the most important emissions from roads, leading to a reduction in breeding bird density along roads (Reijnen et al. 1995a). The effect distance of reduced breeding bird density can be calculated according to the model by Reijnen et al. (1995b):

$$d = c \cdot \sqrt{x + a} - b \qquad (7)$$

where x is traffic volume in number of vehicles per day, d is the effect distance, and a and b are constants. When the percentage of forested areas in the region investigated is between 30% and 50% (as in Baden-Württemberg) the specific formula for federal highways, and state, rural, and municipal roads is given by

$$d = 2.531\text{m} \cdot \sqrt{\frac{x}{\text{veh. per day}} + 3897.4} - 125\text{m} \qquad (8)$$

whereas for federal motorways, the specific formula is

$$d = 3.443\text{m} \cdot \sqrt{\frac{x}{\text{veh. per day}} - 3346.5} + 127\text{m} \qquad (9)$$

We calculated and compared the m_{eff} with and without consideration of noise bands, and when including and excluding municipal roads (denoted as i.m.r. and e.m.r., respectively).

RESULTS

State-wide Overview

The results highlight a strong trend for the landscape in Baden-Württemberg to be increasingly fragmented and built up. Between 1930 and 2004, the m_{eff} has diminished from 22.92 km² to 13.01 km² (including municipal roads), a reduction of 43% (Table 1). Excluding municipals roads, the loss amounted to 38% with the m_{eff} reduced from 31.6 km² to 19.58 km² (Fig. 2).

In 2004, most of Baden-Württemberg was covered with patches 16 km² or less in area when municipal roads were included (Fig. 3). The three lowest size categories accounted for approximately 70% of the total state. The smallest patches occurred more frequently in the environs of the cities (Stuttgart, Mannheim, Karlsruhe, Heilbronn, Ulm) and along the river valleys (Rhine, Neckar, Danube), as well as in the northeast and southeast regions. The largest patches were situated in the northern Black Forest, including several unfragmented areas (UFAs) over 100 km² in area. Without considering municipal roads, there were eight UFAs, covering a total area of only 1106 km² (3.1% of the state; Table 1). When municipal roads were included, only six UFAs with a total area of 764 km² were found (2.1% of the state).

Patches between 50 and 100 km² cover the entire Black Forest and large portions of the Swabian Alb. However, the number of areas greater than 50 km² dropped after 1930 from 83 patches (e.m.r.) to 39 patches in 2004 (Table 1). This means that 53% of

Table 1. Data on the development of the degree of landscape fragmentation in Baden-Württemberg. The results include the effective mesh size (m_{eff}), the number of patches included in the calculation, the size of the largest remaining unfragmented patch, and the number of patches >100 km² and >50 km² (for comparison with other analyses; the last column "patches >50 km²" includes the patches >100 km²; e.m.r. = excluding municipal roads; i.m.r. = including municipal roads). Noise bands were excluded (upper half of the table) and included (lower half; for the years 1966, 1977, and 1989; data on traffic volume were only available for these three points in time), respectively. All values are based on the cutting-out (CUT) procedure.

Noise bands / Municipal roads	Year	m_{eff}	Number of patches (>100 m²)	Size of the largest patch	Patches >100 km² number (area / % of the state area)	Patches >50 km² number (area / % of the state area)
without noise bands						
e. m. r.	2004	19.58 km²	21 994	160.10 km²	8 (1106 km²/3.1%)	39 (3138 km²/8.8%)
	1998	20.24 km²	13 945	161.00 km²	8 (1109 km²/3.1%)	40 (3209 km²/9.0%)
	1989	20.51 km²	15 469	161.03 km²	8 (1110 km²/3.1%)	41 (3302 km²/9.2%)
	1977	22.14 km²	15 079	163.40 km²	8 (1115 km²/3.1%)	49 (3846 km²/10.8%)
	1966	24.26 km²	14 352	163.54 km²	11 (1522 km²/4.3%)	54 (4343 km²/12.1%)
	1930	31.47 km²	11 558	221.87 km²	17 (2369 km²/6.6%)	83 (6703 km²/18.7%)
i. m. r.	2004	13.01 km²	40 923	142.30 km²	6 (764 km²/2.1%)	22 (1867 km²/5.2%)
	1998	13.66 km²	30 835	146.70 km²	6 (752 km²/2.1%)	22 (1880 km²/5.3%)
	1989	13.99 km²	34 096	146.83 km²	6 (753 km²/2.1%)	23 (1941 km²/5.4%)
	1977	17.80 km²	33 664	161.39 km²	7 (973 km²/2.7%)	36 (2875 km²/8.0%)
	1966	19.46 km²	34 525	161.49 km²	7 (975 km²/2.7%)	39 (3068 km²/8.6%)
	1930	22.92 km²	32 049	206.20 km²	11 (1497 km²/4.2%)	52 (4067 km²/11.8%)
with noise bands						
e. m. r.	1989	19.40 km²	11 958	160.84 km²	8 (1104 km²/3.1%)	38 (3084 km²/8.6%)
	1977	21.67 km²	12 820	163.24 km²	8 (1112 km²/3.1%)	48 (3779 km²/10.6%)
	1966	24.04 km²	12 913	161.49 km²	11 (1522 km²/4.3%)	54 (4340 km²/12.1%)
i. m. r.	1989	13.34 km²	27 575	146.25 km²	6 (751 km²/2.1%)	22 (1871 km²/5.2%)
	1977	17.45 km²	29 682	161.22 km²	7 (972 km²/2.7%)	35 (2816 km²/7.9%)
	1966	19.35 km²	31 981	161.49 km²	7 (975 km²/2.7%)	39 (3067 km²/8.6%)

Fig. 2. Time series of the degree of landscape fragmentation in Baden-Württemberg since 1930, obtained by using the effective mesh size (m_{eff}; in km²); e.m.r. = excluding municipal roads (upper curve), i.m.r. = including municipal roads (lower curve); with and without noise bands (data on traffic volume were available for only three points in time). The lower the value of the m_{eff} the higher the degree of landscape fragmentation.

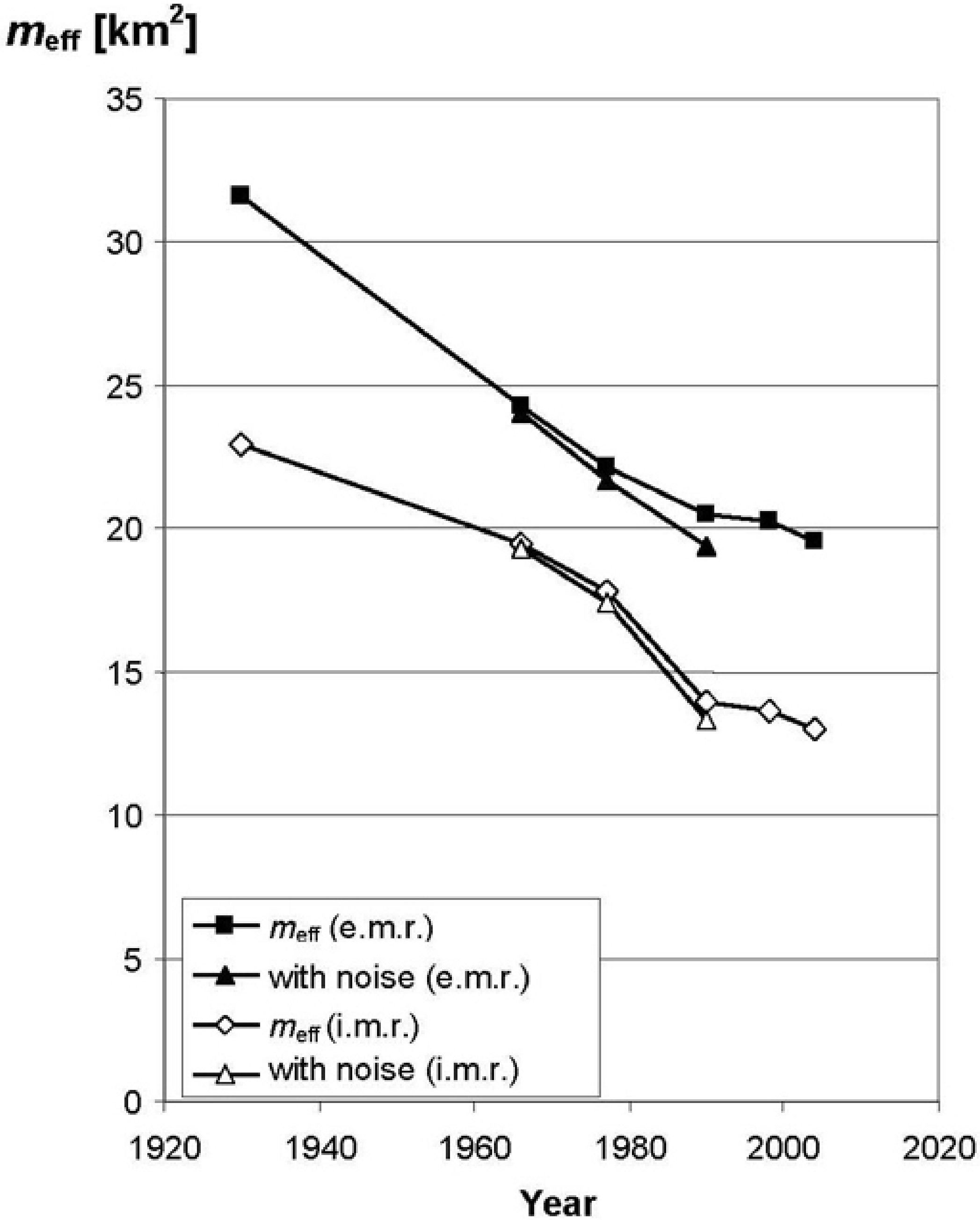
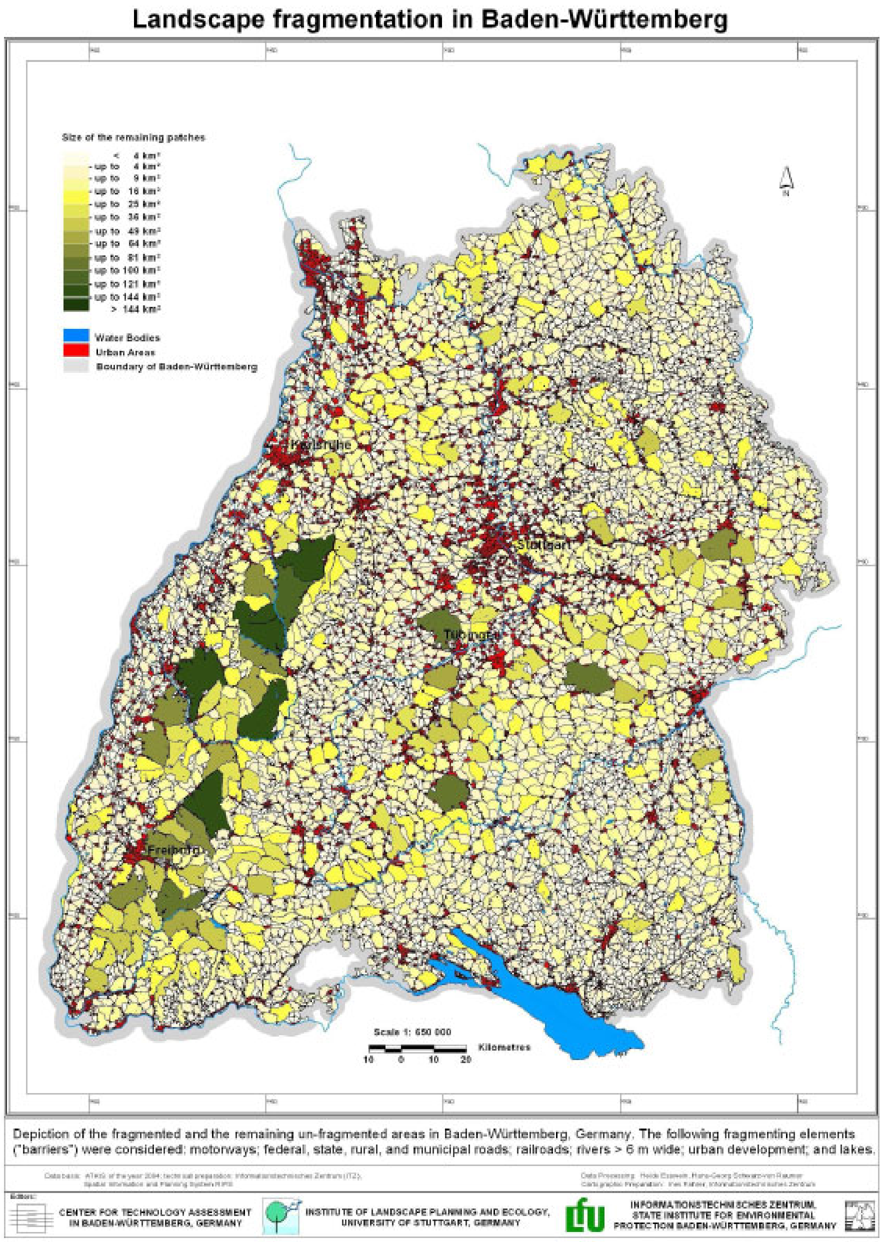


Fig. 3. Landscape fragmentation due to transportation infrastructure and urban development in Baden-Württemberg in 2004. The colors of the patches indicate their sizes. Only six patches >100 km² and 22 patches >50 km² remain. The following fragmenting elements (barriers) were considered: motorways; federal, state, rural, and municipal roads; railroads; rivers >6 m wide; urban development; and lakes. (Click here to view or download a high resolution pdf version. File size: 1301 KB)



the UFAs over 50 km² have been lost since 1930. When municipal roads were included, the reduction was even greater: the number of patches over 50 km² was reduced from 52 to 22, i.e., a 56% reduction (Table 1).

With the inclusion of municipal roads, there were still 11 patches of over 100 km² in 1930, one of them even >200 km² (206.2 km²). With the exclusion of municipal roads, the number of UFAs over 100 km² dropped from 17 to 8 (over 50%). When the decrease in the number of UFAs >50 km² since 1930 was extrapolated linearly into the future, all these areas were expected to be lost by the year 2070. Linear extrapolation for the trend of the m_{eff} decreasing by more than 40% since 1930 (including municipal roads) predicted a m_{eff} of 0 for the year 2100. However, a linear extrapolation of the m_{eff} is an unrealistic scenario.

The m_{eff} is reduced to 0 only when a landscape has been completely covered by traffic infrastructure and urban development. The measure of the m_{eff} reacts more slowly as it approaches 0. To overcome this effect, the effective mesh density, *s*, can be used, which also is a measure of fragmentation that increases with increasing fragmentation (but, unlike the m_{eff}, is not area-proportionately additive; see Jaeger 2000, 2002: 153–168). The m_{eff} and *s* stand in the relation of $s = 1/m_{eff}$. Consequently, linear extrapolations of the *s*, rather than the m_{eff}, would produce much more realistic scenarios for future development under business-as-usual conditions.

The Four Main Administrative Units

The decline of the m_{eff} is obvious in all the administrative districts, whereas the gradient of the graphs is variable (Fig. 4).

In Fig. 4a, the development of the m_{eff} within the administrative districts is particularly interesting in Stuttgart and Tübingen (without municipal roads). At first, Tübingen started off on a slightly lower level than Stuttgart; however, by 1966, this sequence was reversed. Thereafter, the difference between the two districts remained somewhat greater, but by 1989, Tübingen came very close to Stuttgart again. The Freiburg and Karlsruhe districts reflected the graphs for Baden-Württemberg as a whole (Fig. 2). The large difference in m_{eff} (by approximately 15 km²) between Freiburg and the other three districts was due to the number of large unfragmented spaces within the Freiburg district. The percent decrease of m_{eff} was greatest in the district of Stuttgart (Table 2), followed by Karlsruhe and Freiburg.

When municipal roads were included, two different kinds of development were observed (Fig. 4b). In Freiburg and Tübingen, fragmentation did not increase very much until after 1977, but in Karlsruhe and Stuttgart the process began after 1966. Here again the percent decrease of m_{eff} was greatest in Stuttgart. The district of Freiburg moved into second place, showing a decrease of -47% (Table 2). Karlsruhe was the only district showing a better result here than on the e.m.r. level.

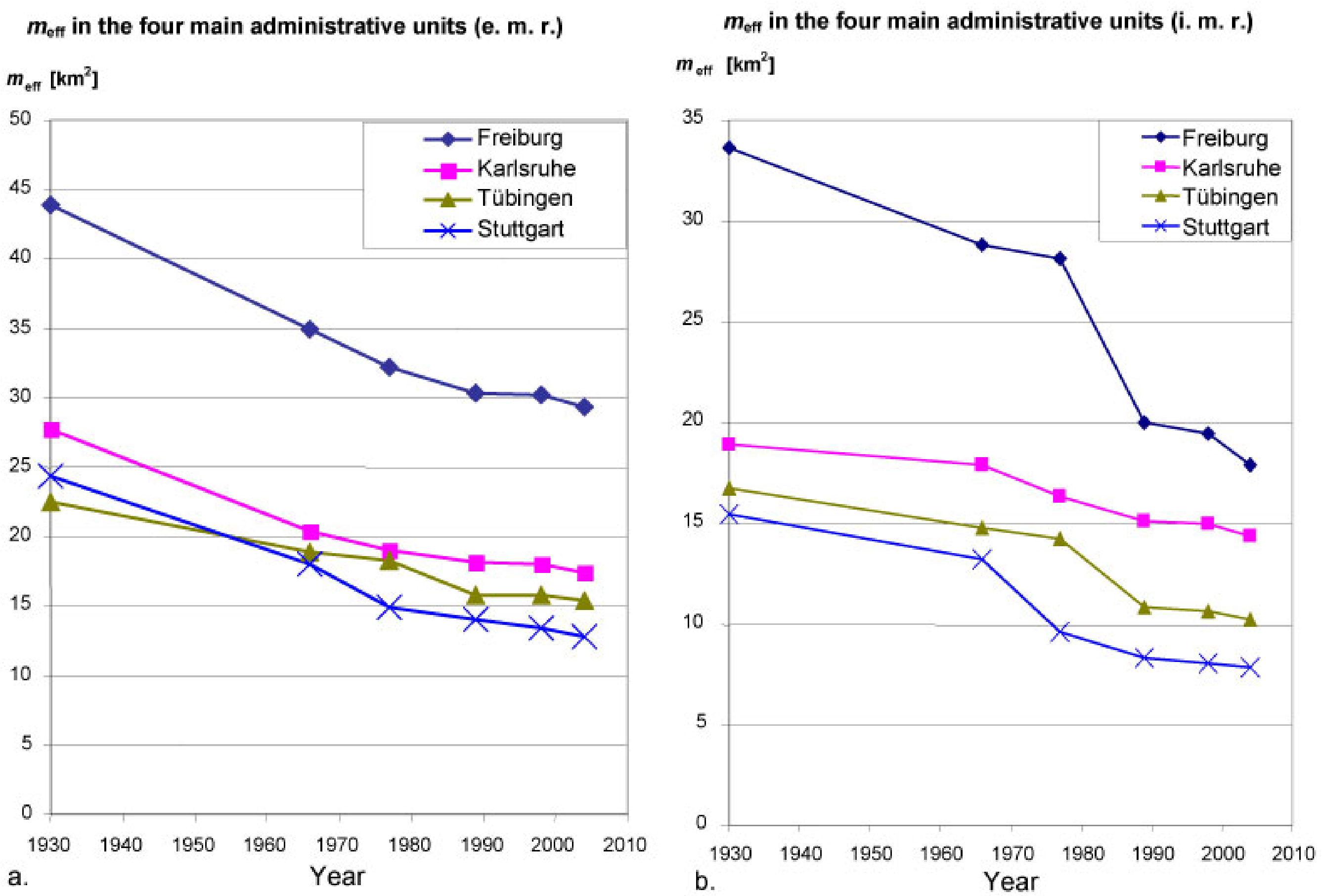
District Level (“Landkreise”)

In this section, the same investigation concept as in the previous section (i.e., administrative units) is followed, but it was conducted at a finer scale (Fig. 5). The highly urbanized districts, such as Stuttgart, Mannheim, and Ulm, are obviously the most fragmented ones, whereas the least fragmented ones are located in the Black Forest (e.g., Ortenaukreis, Freudenstadt, and Emmendingen).

The development of landscape fragmentation exhibits strong regional differences. Of the rural districts, or counties, 27% (12 in all) suffered a decrease of over 50% (including municipal roads). These included urban districts such as Karlsruhe (-69%), Ulm (-66%), Stuttgart (-61%), Pforzheim (-59%), and Heilbronn (-62%), as well as strongly urbanized districts, such as Göppingen (-64%) and Rems-Murr (-59%). Even the more rural areas, such as the Bodensee (Lake Constance) district (-60%), Waldshut (-53%), Schwäbisch Hall (-48%), and Hohenlohe (-55%), displayed great changes in m_{eff}. Only two districts showed a relatively small decrease of less than 20% (Baden-Baden and Freudenstadt).

For the e.m.r. situation, five districts showed a percent decrease in m_{eff} of more than 65% from 1930 to 2004 (Table 3). At this level, the leaders in increased landscape fragmentation were the urban districts of Ulm, Stuttgart, Karlsruhe (town), Heilbronn (town), and Göppingen. A decrease of 50% or more also occurred in the Esslingen, Heidelberg (town), Heilbronn (country), Karlsruhe (country), Rhein-Neckar, Mannheim, and Schwarzwald-Baar districts.

Fig. 4. Time series of the degree of landscape fragmentation in terms of effective mesh size (m_{eff}) within the four administrative districts in Baden-Württemberg from 1930 to 2004 (in km²; without noise bands). a: excluding municipal roads; b: including municipal roads.



The difference between the CTRP procedure and CUT procedures is illustrated by comparing the two methods using the 2004 data at the district level (Fig. 5). The comparison demonstrated the strong influence exerted by the patches located at the boundaries of the region under observation. In general, the larger the region under observation and the smaller the patches located at the boundaries, the smaller the difference between the two methods. The CUT procedure almost always led to lower values of m_{eff} than the CTRP procedure. The differences between the two values vary. This is because the CTRP procedure artificially dissects patches at the boundaries of the districts, whereas the CTRP procedure assigns those patches entirely to a district. If there are large patches at the boundary, the effect on the value of the m_{eff} can be accordingly large. For example, those districts in the Black Forest that were fragmented to a lesser extent (with m_{eff} >10 km²) such as Baden-Baden, Freudenstadt, Rastatt, or Emmendingen, exhibited relatively large differences between the two procedures (Fig. 5). However, in one district, Calw, the opposite effect occurred because the central point of a relatively large patch on the border of the district was located in the neighboring district. Therefore, the patch was not assigned to the Calw district by the CTRP procedure, but a significant

Table 2. Data on the development of the degree of landscape fragmentation in the four main administrative units of Baden-Württemberg (e.m.r. = excluding municipal roads; i.m.r. = including municipal roads; for the years 1966, 1977, and 1989, a comparison with/without noise bands was included). All values are based on the cutting-out (CUT) procedure.

		Effective mesh size m_{eff} (in km²)										
Municipal roads	Admin. unit	1930	1966	1966 with noise bands	1977	1977 with noise bands	1989	1989 with noise bands	Change in 1989 with noise bands since 1930	1998	2004	Change in 2004 since 1930
e.m.r.	Freiburg	43.92	34.96	34.78	32.24	31.71	30.31	29.20	-34%	30.28	29.32	-33%
	Karlsruhe	27.68	20.36	20.03	19.08	18.46	18.15	17.25	-38%	17.98	17.42	-37%
	Tübingen	22.56	18.92	18.79	18.32	18.11	15.84	15.36	-32%	15.81	15.38	-32%
	Stuttgart	24.39	18.06	17.79	14.94	14.46	14.09	12.59	-48%	13.41	12.82	-47%
i.m.r.	Freiburg	33.63	28.83	28.70	28.16	27.77	20.01	19.36	-42%	19.49	17.91	-47%
	Karlsruhe	18.93	17.9	17.61	16.33	15.88	15.15	14.45	-24%	14.99	14.39	-24%
	Tübingen	16.73	14.77	14.68	14.25	14.08	10.87	10.54	-37%	10.62	10.27	-39%
	Stuttgart	15.45	13.2	12.99	9.63	9.28	8.37	7.61	-51%	8.08	7.88	-49%

part of it was attributed to Calw by the CUT procedure.

The 66 Ecoregions

Among the ecoregions, the differences were even stronger than among the administrative units (Fig. 6). The ecoregions along the river valleys (Neckar-Rheinebene, Hessische Rheinebene, Unteres Illertal) and those ecoregions that are dominated by urban agglomerations (e.g., Stuttgarter Bucht, Filder, and Bergstrasse) all had values below 3.5 km² (i.m.r.). The highest value was found in the Grindenschwarzwald und Enzhöhen with 67.08 km² (i.m.r.). Marked differences between the two procedures (CTRP and CUT procedures) affected only a small number of ecoregions that are situated in the Black Forest.

The increases in landscape fragmentation since 1930 were often very high (Fig. 7). Excluding the municipal roads, the following ecoregions showed the largest decreases in m_{eff}: Hardtebenen (-82%), Hessische Rheinebene (-79%), Stuttgarter Bucht (-77%), Neckar-Rheinebene (-71%), Mittleres Albvorland (-66%), and the Baar (-65%). Most of these areas are situated close to the growing suburbs of Stuttgart and in the river valleys, where the industrial development occurred. Five areas in the Black Forest showed a decrease of less than 10%: Grindenschwarzwald und Enzhöhen (-6%), Nördlicher Talschwarzwald (-9%), Baaralb und Oberes Donautal (-9%), the Markgräfler Hügelland (-9%), and Vorderer Odenwald (-7%). When the municipal roads were included, the following areas showed the biggest loss in m_{eff}: Neckar-Rheinebene (-73%), Mittelfränkisches Becken (-68%), Hessische Rheinebene (-68%), and Markgräfler Rheinebene (-68%). In all, 23 ecoregions showed a decline in m_{eff} of over 50% (Fig. 7). This is more than twice the number for the e.m.r. level (only 9).

The development of the m_{eff} within the ecoregions clearly shows how the graph for the whole of Baden-Württemberg (Fig. 3) is made up. The various

Fig. 5. Data on the current (2004) degree of landscape fragmentation in the 44 rural districts of Baden-Württemberg (including municipal roads). Two methods were compared: the cutting-out (CUT) procedure (dark bars) and the central-point (CTRP) procedure (light bars; see text for explanation of the methods). The order of the rural districts is according to increasing values of the effective mesh size (m_{eff}) as measured by the CUT procedure. For comparisons, the value of the m_{eff} of the entire state of Baden-Württemberg is shown by a solid line (13.01 km²).

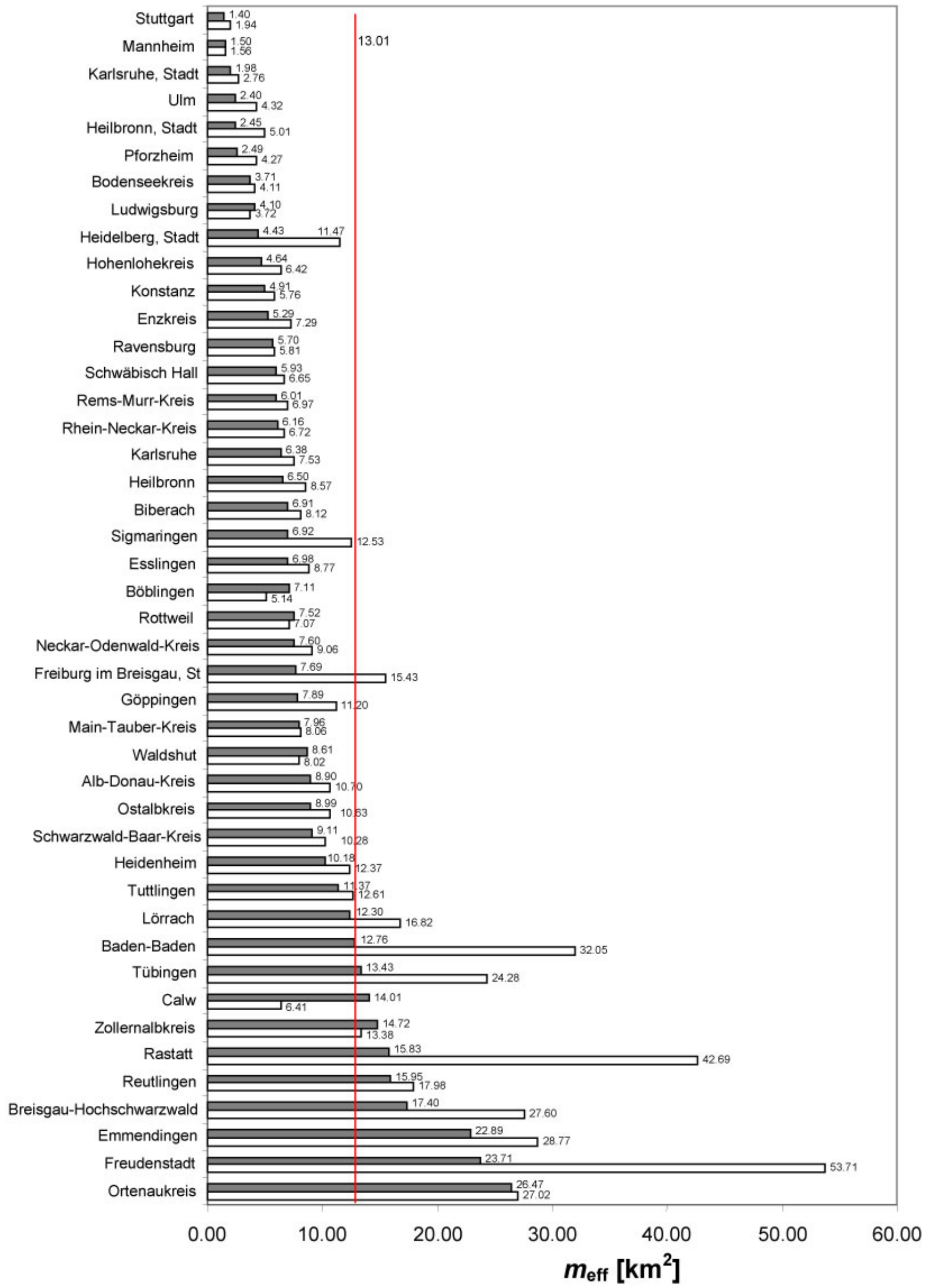


Table 3. Data on the development of the degree of landscape fragmentation in the 44 rural districts, or counties, of Baden-Württemberg (excluding municipal roads); for the years 1966, 1977, and 1989, a comparison with and without noise bands was included. All values are based on the cutting-out (CUT) procedure.

Effective mesh size (m_{eff}; in km²), fragmentation level excluding municipal roads											
Rural district	1930	1966	1966 with noise bands	1977	1977 with n-oise b-ands	1989	1989 with noise ba-nds	change from 1930 to 1989 with noise bands	1998	2004	change from 1930 to 2004
Alb-Donau-Kreis	20.02	18.66	18.21	15.88	15.39	13.78	12.89	-36%	13.74	13.54	-32%
Baden-Baden	16.21	15.28	15.02	15.13	14.84	13.72	13.26	-18%	13.67	13.55	-16%
Biberach	12.49	11.98	11.98	11.07	11.04	10.52	10.39	-17%	10.51	10.25	-18%
Böblingen	12.66	9.98	9.61	8.85	8.02	8.81	6.88	-46%	8.82	8.11	-35%
Bodenseekreis	10.58	9.12	9.03	8.83	8.73	7.51	7.08	-33%	7.5	7.28	-31%
Breisg.-Hochschw.	38.80	29.54	29.23	27.80	26.88	27.80	26.40	-32%	27.66	26.82	-31%
Calw	23.11	20.46	20.46	20.05	20.03	18.66	18.53	-20%	18.49	18.34	-21%
Emmendingen	47.13	33.30	33.14	32.90	32.29	32.63	31.80	-33%	32.62	31.61	-33%
Enzkreis	9.99	7.12	6.76	6.46	5.98	6.09	5.46	-45%	6.02	5.83	-42%
Esslingen	20.27	10.54	9.73	8.75	7.72	8.16	6.50	-68%	8.16	7.82	-61%
Freiburg i. B., St.	12.55	9.69	8.99	9.57	8.34	9.05	7.67	-39%	9.03	8.13	-35%
Freudenstadt	28.86	26.90	26.89	26.64	26.64	26.54	26.35	-9%	26.43	25.91	-10%
Göppingen	35.98	15.70	14.95	15.46	14.65	11.60	10.32	-71%	11.57	11.48	-68%
Heidelberg, Stadt	11.89	7.26	6.63	5.57	5.15	5.45	4.97	-58%	5.40	5.34	-55%
Heidenheim	23.07	21.70	21.66	20.15	20.11	20.64	19.00	-18%	18.37	18.10	-22%
Heilbronn	17.03	11.25	10.93	8.63	7.78	8.39	7.08	-58%	8.19	7.86	-54%
Heilbronn, Stadt	9.77	4.07	4.00	3.41	2.67	3.30	2.04	-79%	3.22	3.08	-68%
Hohenlohekreis	13.14	10.17	10.17	9.94	9.90	8.99	8.60	-35%	8.94	8.58	-35%
Karlsruhe	18.22	11.20	10.61	11.27	10.51	9.37	8.17	-55%	9	8.02	-56%
Karlsruhe, Stadt	9.59	3.43	2.72	4.20	2.33	2.92	1.77	-82%	2.74	2.43	-75%
Konstanz	11.13	9.77	9.77	9.26	9.06	7.63	6.98	-37%	7.52	7.38	-34%
Lörrach	22.18	20.93	20.84	20.95	20.75	20.69	19.89	-10%	20.66	20.25	-9%
Ludwigsburg	8.21	7.24	6.92	6.03	5.56	5.10	4.47	-46%	5.05	4.62	-44%

(con'd)

Main-Tauber-Kr.	21.28	17.95	17.95	14.33	13.97	13.90	13.61	-36%	13.86	13.38	-37%
Mannheim	4.08	2.24	1.41	2.23	1.17	2.12	0.92	-77%	2.09	1.81	-56%
Neckar-Od.w.-Kr.	25.74	17.84	17.80	15.53	15.41	14.24	13.95	-46%	14.2	13.86	-46%
Ortenaukreis	57.33	53.17	52.78	47.20	46.25	46.22	44.47	-22%	46.13	44.55	-22%
Ostalbkreis	27.97	28.35	28.34	19.54	19.38	18.38	14.62	-48%	15.31	14.35	-49%
Pforzheim	8.46	6.68	5.79	6.13	4.85	5.95	4.52	-47%	5.9	5.81	-31%
Rastatt	23.53	19.12	18.92	18.66	18.27	18.49	17.70	-25%	18.4	17.66	-25%
Ravensburg	13.09	11.50	11.50	11.40	11.36	10.76	10.34	-21%	10.57	9.73	-26%
Rems-Murr-Kreis	19.51	13.72	13.40	12.38	12.12	11.94	11.43	-41%	11.8	11.56	-41%
Reutlingen	27.02	23.05	23.02	22.97	22.83	22.63	22.33	-17%	22.58	22.45	-17%
Rhein-Neckar-Kr.	17.24	10.17	9.89	8.15	7.03	7.74	6.19	-64%	7.71	7.12	-59%
Rottweil	23.23	16.04	16.04	14.29	14.29	12.56	11.72	-50%	12.84	11.68	-50%
Schwäbisch Hall	17.35	12.80	12.80	11.66	11.66	11.52	11.16	-36%	11.48	10.90	-37%
Schwarzw.-B.-Kr.	34.57	25.34	25.34	22.07	21.90	17.32	16.67	-52%	17.39	17.00	-51%
Sigmaringen	17.57	15.62	15.62	16.32	16.32	11.70	11.65	-34%	11.85	11.49	-35%
Stuttgart	10.97	4.25	3.16	4.35	3.22	2.92	1.72	-84%	3.34	2.52	-77%
Tübingen	23.06	20.18	20.04	19.67	18.98	17.95	16.59	-28%	17.9	17.59	-24%
Tuttlingen	22.70	21.08	21.08	20.18	19.87	17.64	16.79	-26%	17.61	17.32	-24%
Ulm	14.12	7.75	6.77	5.62	5.07	3.16	2.53	-82%	3.11	3.04	-78%
Waldshut	20.04	17.81	17.81	17.01	17.00	16.68	16.58	-17%	16.69	16.27	-19%
Zollernalbkreis	28.20	19.71	19.66	19.58	19.33	18.53	17.98	-36%	18.51	17.97	-36%

ecoregions have experienced quite different developments, some even deviating strongly from the general trend (Fig. 8). In many cases, a marked increase in fragmentation had already occurred between 1930 and 1966. The Neckar-Rheinebene, Stuttgarter Bucht, Hessische Rheinebene, Filder, Mittleres Albvorland, Hardtebenen, and Baar evidently experienced a decrease in m_{eff} during this period. These are often the areas that have also suffered the largest overall loss since 1930. However, the östliches Albvorland and Marktheidenfelder Platte do not show significant changes until after 1966, this development continuing to a lesser extent in the östliches Albvorland, although the m_{eff} in the Marktheidenfelder Platte ecoregion barely changes from that of 1966.

Example of How an Area’s Sensitivity to Fragmentation Can Be Taken into Account

Fragmentation measures will more likely prove useful for planning purposes when the results are coupled with a sensitivity survey that identifies those areas that are most likely to be adversely affected by fragmentation (e.g., because recreational quality is restricted or opportunities for movement

Fig. 6. The current (2004) degree of landscape fragmentation in the 66 ecoregions, or natural landscape units, in Baden-Württemberg (fragmentation level including municipal roads), in terms of the effective mesh size (m_{eff}; in km²). The figures (identification numbers) identify the ecoregions (in alphabetical order): Adelegg (34), Albuch und Härtsfeld (96), Alb-Wutach-Gebiet (120), Baar (121), Baaralb und Oberes Donautal (92), Bauland (128), Bergstrasse (226), Bodenseebecken (31), Die Filder (106), Dinkelberg (161), Donau-Ablach-Platten (40), Donauried (45), Frankenhöhe (114), Freiburger Bucht (202), Grindenschwarzwald und Enzhöhen (151), Hardtebenen (223), Hegau (30), Hegaualb (91), Hessische Rheinebene (225), Hochrheintal (160), Hochschwarzwald (155), Hohe Schwabenalb (93)¸ Hohenloher-Haller-Ebene (127)¸ Holzstöcke (43), Hügelland der unteren Riss (42), Kaiserstuhl (203), Kocher-Jagst-Ebene (126), Kraichgau (125), Lahr-Emmendinger Vorberge (211), Lonetal-Flächenalb (97), Markgräfler Hügelland (201), Markgräfler Rheinebene (200), Marktheidenfelder Platte (132), Mittelfränkisches Becken (113), Mittlere Flächenalb (94), Mittlere Kuppenalb (95), Mittlerer Schwarzwald (153), Mittleres Albvorland (101), Neckarbecken (123), Neckar-Rheinebene (224), Nördliche Oberrhein-Niederung (222), Nördlicher Talschwarzwald (152)¸ Obere Gäue (122), Oberschwäbisches Hügelland (32), Ochsenfurter- und Gollachgau (130), Offenburger Rheinebene (210), Ortenau-Bühler Vorberge (212), Östliches Albvorland (102), Randen (90), Ries (103), Ries-Alb (98), Riss-Aitrach-Platten (41), Sandstein-Odenwald (144), Sandstein-Spessart (141), Schönbuch und Glemswald (104)¸ Schurwald und Welzheimer Wald (107), Schwäbisch-Fränkische Waldberge (108), Schwarzwald-Randplatten (150), Strom- und Heuchelberg (124), Stuttgarter Bucht (105), Südöstlicher Schwarzwald (154), Südwestliches Albvorland (100), Tauberland (129), Unteres Illertal (44), Vorderer Odenwald (145), Westallgäuer Hügelland (33). (Click here to view or download a high resolution pdf version. File size: 252 KB)

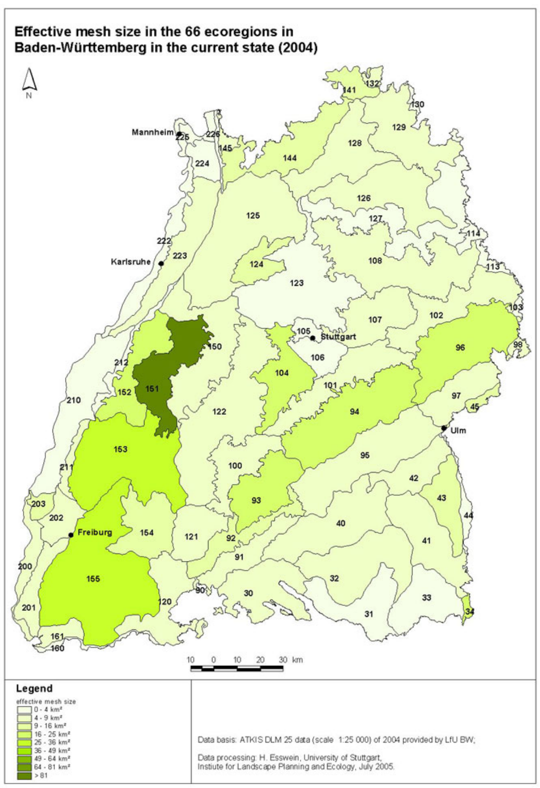


Fig. 7. Development of the degree of landscape fragmentation in terms of effective mesh size (m_{eff}; in km²) within the 66 ecoregions, or natural landscape units, in Baden-Württemberg from 1930 to 2004 (fragmentation level "including municipal roads"). The change in m_{eff} is expressed as a percentage of the 1930 results. The identification numbers and names of the ecoregions are given in the legend to Fig. 6. (Click here to view or download a high resolution pdf version. File size: 269 KB)

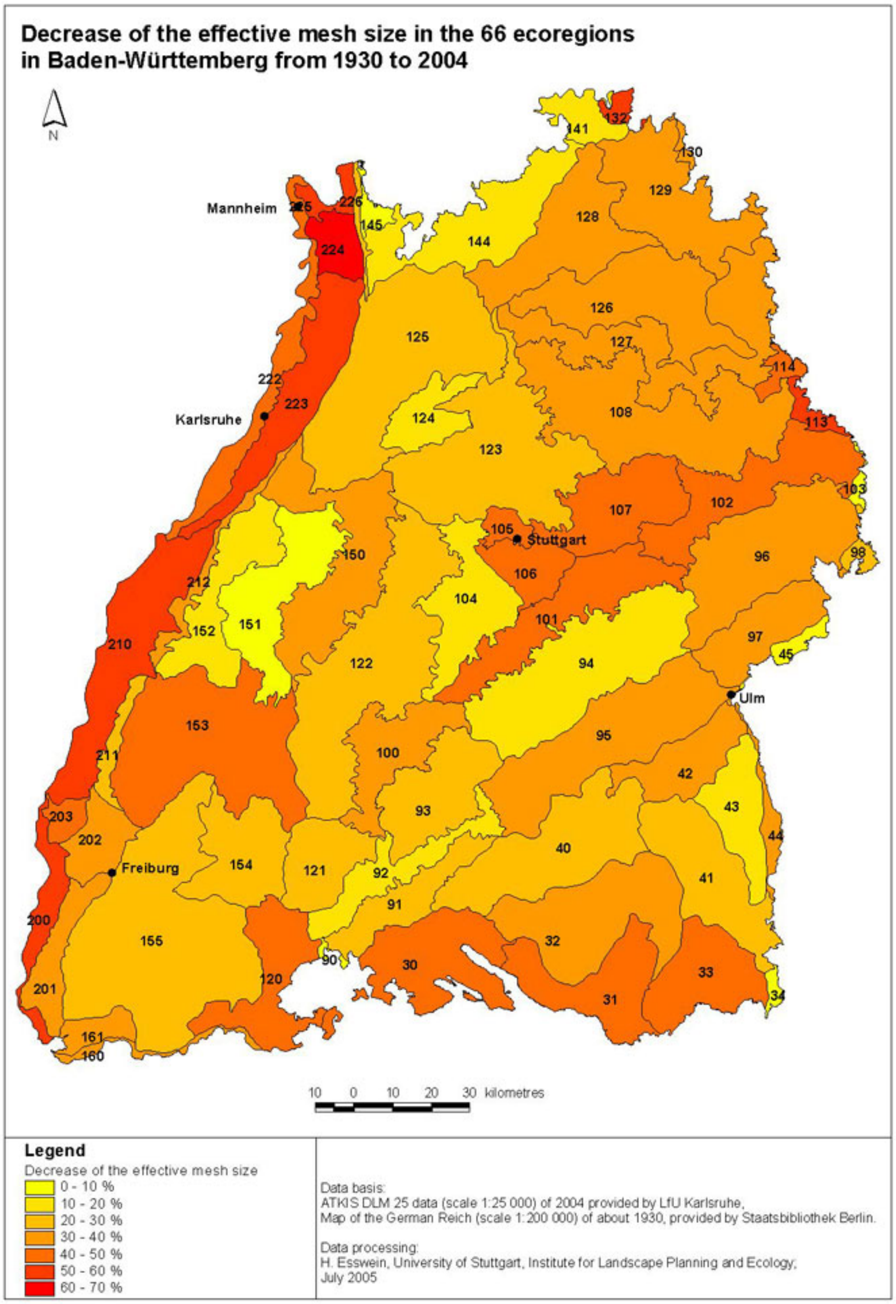
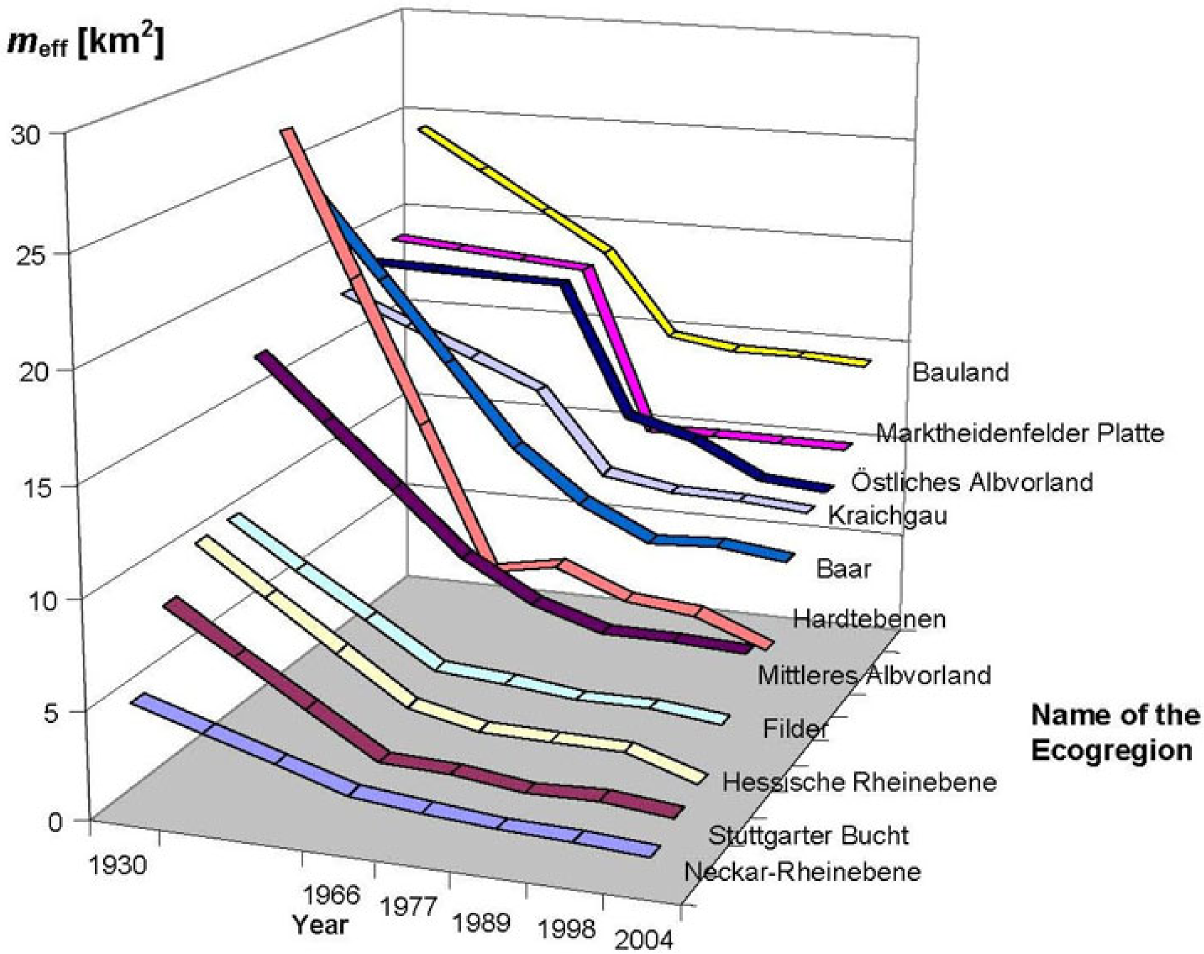


Fig. 8. Some examples of time series of the degree of landscape fragmentation within the ecoregions in Baden-Württemberg from 1930 to 2004 in terms of effective mesh size (m_{eff}; in km²; fragmentation level excluding municipal roads). (The location of the ecoregions within Baden-Württemberg is shown in Fig. 6.)



between habitats or subpopulations are reduced). Fragmentation particularly affects those animal species needing a combination of various landscape elements or particular landscape structures, as well as those whose regional survival depends on successful metapopulation dynamics. However, at the regional planning scale, it is not presently feasible to obtain a large-scale description of sensitivity to fragmentation based on actual movement patterns of animal species. Instead, spatial categories, displaying a high probability of vulnerable movement patterns, can be identified. This task may include the use of models (e.g., Vuilleumier and Prélaz-Droux, 2002).

Large connected areas of forests may serve as an initial, if crude, categorization of areas sensitive to fragmentation that are easy to define and delimit. A second category that is useful at the regional planning scale is provided by Baden-Württemberg's landscape framework program's atlas of maps (IER/ILPö, 1999), showing "areas with a high density of biotopes deserving protection," i.e., areas that exhibit a density of biotopes deserving protection or of state-wide endangered species that is above average. They comprise 26.6% of the state area and have differing degrees of fragmentation (Fig. 9). In total, the m_{eff} of these areas is 17.16 km² whereas the areas outside have a value of 9.05 km², which is much lower, i.e., they are more fragmented (on the i.m.r. level).

Three more options for defining categories that are useful for sensitivity assessments are:

(a) habitats of target species (e.g., Western capercaillie, and lynx) or groups of target species that are particularly vulnerable to fragmentation;

(b) areas that function as corridors that are also particularly vulnerable to fragmentation (e.g., the map of "areas and corridors that are particularly suited for a large-scale connected system of habitats" in the atlas of maps of Baden-Württemberg's landscape framework program (IER/ILPö 1999));

(c) combinations of various types of protected areas that define areas deserving preservation (e.g., areas of landscape protection and priority areas for nature and landscape).

DISCUSSION

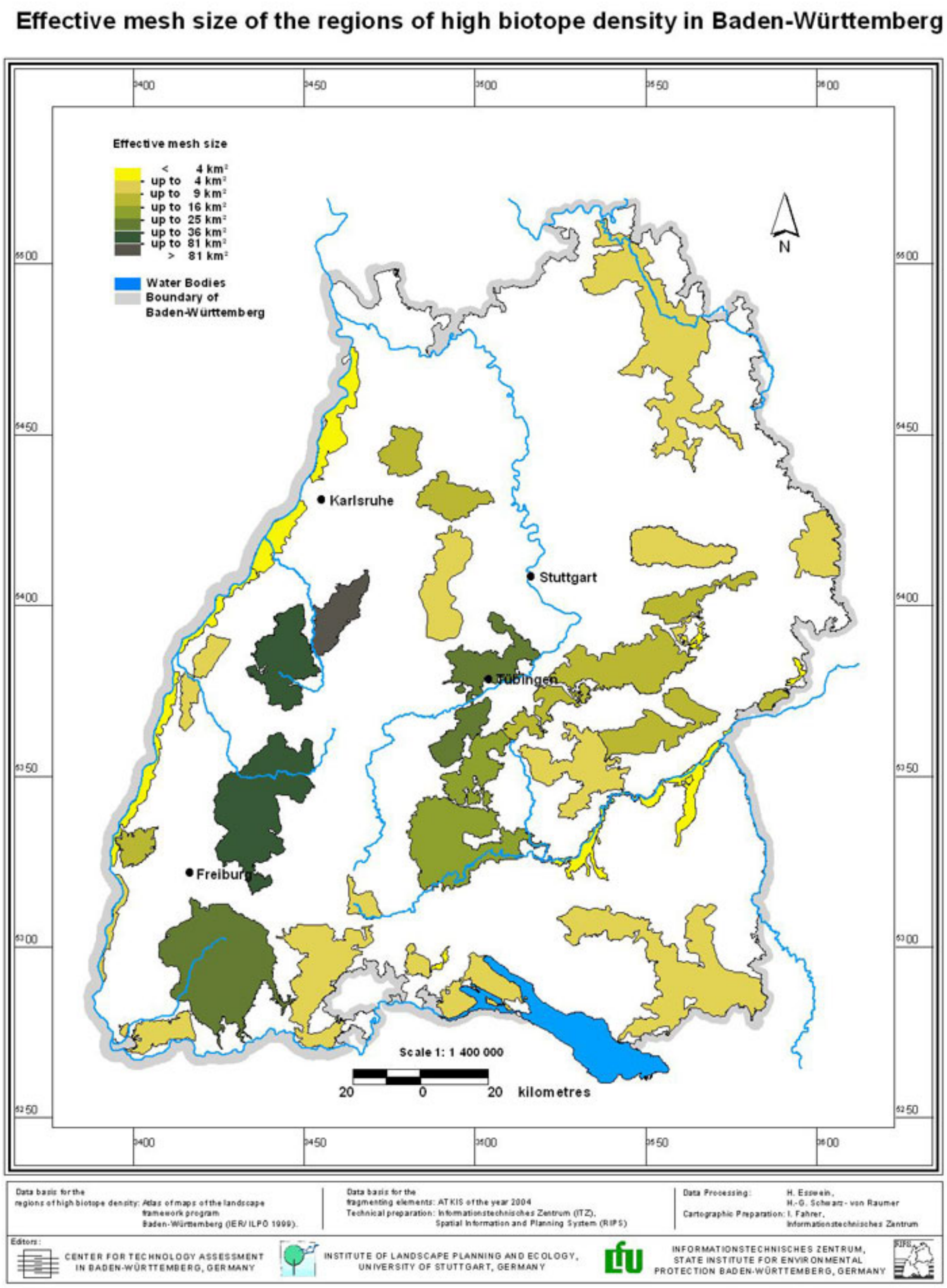
Baden-Württemberg has been fragmented to a far greater extent than indicated by previous analyses (see below). The m_{eff} in Baden-Württemberg has decreased by 43% since 1930, from 22.92 km² to 13.01 km² when municipal roads were included. The road network was already fairly dense by 1930. However, the standard of road construction and the intensity of road use (including noise, etc.) were much lower than they are today. The results thus express a conservative estimate of the increase in landscape fragmentation. The number of UFAs >100 km², i.m.r., has been reduced from 11 in 1930 (4.2% of the state area) to 6 today (2.1% of the state area), and the number of UFAs >50 km² showed a similar trend, an overall reduction of UFAs by 50%–54% within 70 years.

The results demonstrate that Baden-Württemberg has now reached a very high level of fragmentation. They provide clear answers to the questions posed in the introduction about the range of the degree of fragmentation among the various regions in Baden-Württemberg, the ranking order of the regions, and how quickly the degree of fragmentation has changed since 1930. The degree of fragmentation covered a very wide range: the m_{eff} was between 1.4 km² and 26.5 km² among the 44 rural districts, or counties, when municipal roads were included. The changes in the degree of fragmentation in different parts of the state differed considerably.

At least six variables appear suitable for explaining these differences: relief (altitude and slope), amount of forest, amount of urban development, population density, degree of motorization, and the aggregation of urban areas and traffic lines. Regions at higher elevations were less fragmented than the valleys. This is a consequence of easier access of lowlands for settling in historic times. For example, the river valleys such as the Rhine valley and the Neckar valley exhibited a much lower m_{eff} than the Swabian Alb (a plateau at a higher altitude) or the Black Forest. In general, flat regions such as the Kocher-Jagst-Ebene, the Filder, and the Lake Constance region were more fragmented than the hilly and mountainous areas.

Roads are increasingly considered relevant in the process of forest fragmentation and loss of forest (Riitters et al. 2004, Wear et al. 2004, Kupfer 2006). In our study, the percentage of forest in the ecoregions exhibiting a m_{eff} of less than 6 km² was mostly between 10% and 30%, whereas the areas with more than 40% forest had a m_{eff} of more than 8 km²; and in the areas with more than 60% forest, the m_{eff} was more than 11 km² (i.m.r.), and there were only a few exceptions. A similar trend was observed for the density of inhabitants. In regions with more then 400 inhabitants per square kilometer, the m_{eff} was less than 5 km². However, there are some substantial exceptions to this pattern as well. For example, in the Schönbuch and Glemswald ecoregion, the m_{eff} was 21.4 km² (490 inhabitants per square kilometer; 60% forest, 9% urban development). In addition, some sparsely populated areas were highly fragmented, e.g., the Hohenloher-Haller-Ebene (190 inhabitants per square kilometer and a m_{eff} of 3.1 km²) and the Oberschwäbisches Hügelland (90 inhabitants per square kilometer and a m_{eff} of 5.7 km²). Widely dispersed urban areas and transportation infrastructure had an important influence contributing to high degrees of fragmentation in these regions as

Fig. 9. Current (2004) degree of landscape fragmentation of the regions with high biotope density in Baden-Württemberg (fragmentation level including municipal roads) in terms of the effective mesh size (m_{eff}; in km²). (Click here to view or download a high resolution pdf version. File size: 288 KB)



opposed to regions where densely populated areas were confined and traffic lines were bundled.

The increase in landscape fragmentation is tightly related to the increase in the human population. At the end of World War II, the number of inhabitants in Baden-Württemberg increased considerably because many people—displaced from their homes—immigrated there from those parts of Eastern Germany that were occupied by Russia, and from Eastern Europe. The population reached 6.43 million in 1950 and continued to grow to 10.27 million in 1995 and 10.74 million in 2006. The areas of urban development doubled between 1950 and 1995 (Jaeger 2002). Baden-Württemberg exhibits a strong trend of increasing numbers of households with only one or two people, and decreasing numbers of households with more than three people, leading to a higher per capita uptake of land for housing.

The development of infrastructure and urban areas in Baden-Württemberg was shaped by the political planning system. At the end of the 19th century, when the number of jobs in the cities (such as Stuttgart, Mannheim, Tübingen, Ulm) increased, the housing areas in the surroundings of these cities mushroomed, and the number of commuters using both public trains and private vehicles exploded. The number of vehicles per 1000 inhabitants climbed from 50 in 1950, to 360 in 1975, and to 696 in 2005 (Statistisches Landesamt 2006). The first motorways in Baden-Württemberg had already been built in the 1930s before World War II, and there are 1037 km of motorway today (Bundesministerium für Verkehr, Bau- und Wohnungswesen 2005). This rapid development of the cities was a signal for the government to regulate the emerging patterns. The system they designed exhibits a hierarchical order of the various categories of urban areas based on the central place theory (Christaller 1933). The centers were determined after a population census in 1950. These centers are connected to each other by development axes that generally carry more traffic than the connections between places of lower hierarchy. This system of decentralized concentration leads to much higher fragmentation of the landscape than centralized systems with one large capital and many rural areas on the periphery, as is observed, e.g., in France.

Our results suggest that using natural boundaries is more appropriate in an ecological perspective because the fragmentation pattern is generally more homogeneous within the ecoregions (e.g., areas within and outside of the Black Forest) than the political districts. Evidence for this conclusion is the observation that the range of values of the m_{eff} was larger among the ecoregions than among the political districts. However, political boundaries have often been considered more relevant for communication by decision makers because people can compare their home district with other districts. Therefore, data on both ecoregions and administrative districts are valuable information for sustainability monitoring.

The municipal roads added considerably to the degree of landscape fragmentation. When municipal roads were included or excluded, the m_{eff} changed by about 30% for all of Baden-Württemberg (changes ranged between 5% and 57% among the 44 rural districts). Therefore, municipal roads should be included in studies on the degree of landscape fragmentation and its effects. However, the general trends over time were very similar in most parts of the state.

Noise bands also had an important influence. More recent points in time exhibited stronger differences in the results including and excluding the noise bands, by 5% for all of Baden-Württemberg for 1989 (between 0.4% and 57% among the rural districts), reflecting an extensive increase in traffic volume over recent decades. Depending on the objectives of the investigation (e.g., quality for recreational use vs. habitat suitability for wildlife), different variants of the method may be most appropriate (e.g., with or without noise bands, including or excluding municipal roads).

Our results demonstrated that an area's boundaries can influence its degree of fragmentation if large patches are located close to the boundary (see also Moser et al. 2007 for data from the South Tyrol, Italy). The larger the region and the smaller the patches, the smaller the differences between the results of the CUT and CTRP procedures. To be able to compare the value of a region's m_{eff} with values from earlier points in time, the boundary of the region investigated has to be the same. A fixed boundary is guaranteed only by the CUT procedure.

The comparison of our results with the number of UFAs >100 km² obtained by the German Federal Agency for Nature Conservation (BfN 1999, Gawlak 2001), which was 28 for the year 1998, shows that Baden-Württemberg is actually much more fragmented than suggested by their study. The difference is because their study considered only roads with a traffic volume of over 1000 vehicles/day as fragmenting elements; furthermore, urban areas were not taken into account.

The analysis by Schumacher and Walz (2000) also shows 28 UFAs >100 km² in Baden-Württemberg (totalling 4400 km² = 12% of the state area). This analysis mainly targeted unfragmented spaces for recreation and tourism, identifying only patches over 50 km². Schumacher and Walz (2000) suggest a minimum size of 100 km² as standard for serene outdoor recreation, following the proposal by Lassen (1979). They identified 193 areas >50 km² (16 100 km² = 45% of the state area, including 28 patches >100 km²). The differences from our results can be partially explained by the fact that Schumacher and Walz excluded rural and municipal roads, railways with no express trains (including the German InterRegio, InterCity, and InterCityExpress types of trains), rivers, and lakes from their study. Thus, a large number of areas that seem to be relatively unfragmented according to the method used by Schumacher and Walz, disappear once the other elements fragmenting the landscape are taken into account.

Analyses of correlations between the degree of fragmentation and the presence of key species by habitat suitability modeling can provide information on the effects of fragmentation. Relationships with the presence or decreasing tendencies of individual species, especially Red-List species, may indicate the degree to which the amount and loss of large UFAs reflect the status of a species. Future refinement of methods should include the success rates of attempts to cross roads, and assess the potential of mitigating fragmentation effects by crossing structures (e.g., Hutter et al. 2001, Forman et al. 2003, van der Grift 2005).

CONCLUSIONS

Mobility of goods and people by motorized vehicles is a highly valued feature in a globalizing economy. Increasing human population, decreasing average household size, and increasing commuter distances are important causes of increasing landscape fragmentation. The population of Baden-Württemberg is still growing today because there are better job conditions there than in the eastern parts of Germany. However, the population is expected to peak in 2012 (or slightly after, depending on the number of immigrants) and then decrease. In 2050, the same number of people will live in Baden-Württemberg as in 1990, i.e., less than today. This has important economic consequences for the maintenance of the transportation infrastructure and a dispersed urban development. Significant parts of the infrastructure that are being constructed today will likely no longer be needed by 2050. Short-term economic interests, which currently conflict with ecological considerations regarding the protection of large UFAs, may change drastically in a few decades and eventually align with ecological imperatives.

The approach of environmental indicators being used in environmental reports and progress reports on sustainability is a major application for the type of data reported in this paper. One of the most comprehensive of these assessments has been the report on “The State of the Nation’s Ecosystems—Measuring the Lands, Waters, and Living Resources of the United States,” which proposes seven indicators of fragmentation and landscape pattern, but suffers from a lack of data on these indicators (Heinz Center 2002, O'Malley et al. 2003, Kupfer 2006). The time series presented in this paper provide successful examples of how to implement and interpret time series of landscape fragmentation, as they have already been implemented in the report on the state of the environment by the State Institute for Environmental Protection Baden-Württemberg (Ministerium für Umwelt und Verkehr Baden-Württemberg and Landesanstalt für Umweltschutz Baden-Württemberg 2003, Umweltministerium Baden-Württemberg and Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg 2006) and in the report on the status of sustainable development in Baden-Württemberg (Renn et al. 2000).

The case study presented in this paper provides a model for analyzing and interpreting the current situation and the development over recent decades in other countries, especially for comparative analyses of similar types of ecoregions. The long-term goal is to generate comparative data for the whole of Europe and North America. These would serve as a basis for drawing up agreements about environmental standards, such as limits, norms, and targets, and for creating appropriate measures to bring about the long-awaited “trend reversal in land consumption and landscape fragmentation” (e.g., Bundesminister des Innern 1985). For this purpose, it is useful to establish time series for making comparisons with previous conditions, including comparisons with or without an increase in traffic volume, and to identify changes in trends. The method used here is well suited to this purpose. The above comparison of the different studies also highlights that a unified method (or at least comparable methods) should be selected or evolved for application throughout Germany and Europe, allowing the German federal states and European regions to be standardized (Schupp 2005).

The m_{eff} method provides a means for setting environmental quality objectives for the future degree of landscape fragmentation (Jaeger 2001). For example, the German Federal Environmental Agency recently has proposed quantitative limits for curtailing landscape fragmentation using the m_{eff} (Umweltbundesamt (UBA) 2003: 301, Penn-Bressel 2005). Other suggestions include a variety of measures to avoid, minimize, mitigate, and compensate for fragmentation effects at different planning stages and on different scales (Iuell et al. 2003, Forman et al. 2003). To set appropriate priorities among these measures, knowledge of fragmentation effects needs to be improved. Examples of research questions that need to be investigated are (Trocmé 2002, Roedenbeck et al. 2007): What are the thresholds relating to the barrier effects? How high a transportation network density is acceptable for a given ecosystem and its component habitats and species? How significant is traffic-related mortality for the sustainability of wildlife populations? What density of fauna passages is required to effectively maintain habitat connectivity? The fact that many negative impacts from habitat fragmentation do not become apparent until decades afterward is a serious obstacle in dealing with these questions, as shown by Findlay and Bourdages (2000) in their research on the effects of road density on species richness in wetlands. This considerable time lag between the impact and the resulting effects implies that the loss of species will likely continue for many more years from today onward following the encroachments already made in the landscape.

The desired change in present trends will only come about if substantial changes are made in traffic and urban development policy. The gap between political declarations of intention concerning landscape fragmentation and urban development, and the actual implementation of policy has only widened during the past 15 years. More effective action must be taken in the form of improving available data, drawing up target agreements on landscape fragmentation, monitoring actual disturbance impacts and success of compensatory measures, and introducing restorative commitments.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/vol12/iss1/art22/responses/

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