Landscape Ecology **15:** 115–130, 2000.

Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation

Jochen A.G. Jaeger
Center of Technology Assessment in Baden-Württemberg, Industriestr. 5, D - 70565 Stuttgart, Germany
*(*author for correspondence, e-mail: jochen.jaeger@ta-akademie.de)*

Received 10 May 1998; Revised 23 December 1998; Accepted 19 April 1999

Key words: effective mesh size, fragmentation phases, landscape division, landscape fragmentation, landscape indices, landscape pattern, quantitative methods, spatial heterogeneity, splitting index

Abstract

Anthropogenic fragmentation of landscapes is known as a major reason for the loss of species in industrialized countries. Landscape fragmentation caused by roads, railway lines, extension of settlement areas, *etc.*, further enhances the dispersion of pollutants and acoustic emissions and affects local climatic conditions, water balance, scenery, and land use. In this study, three new measures of fragmentation are introduced: degree of landscape division (*D*), splitting index (*S*), and effective mesh size (*m*). They characterize the anthropogenic penetration of landscapes from a geometric point of view and are calculated from the distribution function of the remaining patch sizes.

First, *D*, *S*, and *m* are defined, their mathematical properties are discussed, and their reactions to the six fragmentation phases of perforation, incision, dissection, dissipation, shrinkage, and attrition are analysed. Then they are compared with five other known fragmentation indices with respect to nine suitability criteria such as intuitive interpretation, low sensivity to very small patches, monotonous reaction to different fragmentation phases, and detection of structural differences. Their ability to distinguish spatial patterns is illustrated by means of two series of model patterns. In particular, the effective mesh size (*m*), representing an intensive and area-proportionately additive measure, proves to be well suited for comparing the fragmentation of regions with differing total size.

Introduction

Landscape fragmentation results from patchwork conversion and development of sites, e.g., into settlements or other intensively used areas, and from linkage of these sites via linear infrastructure (Harris 1984, p. 4; Saunders et al. 1991; Forman 1995). It produces a series of more or less isolated segments of habitat, ecosystem, or land-use type surrounded by a matrix of more intensively utilized areas and lines which modifies the ecological interrelations between the segments, e.g., act as barriers against the dispersal of animals. Accordingly, not only does it characterize the structural *state* of a landscape, but it is also understood to be a *process* (Forman 1995, p. 407) that results in the disruption of existing ecological connections between spatially separated elements of landscapes (Haber 1993, p. 62f). Examples are water flows and climatically relevant lines of air movement (Saunders et al. 1991). Landscape fragmentation also comprises natural barriers against animal dispersal such as rivers. This is defined here as *geogenic fragmentation*. The focus of previous studies often concentrated on the fragmentation of forests (e.g., Burgess and Sharpe 1981; Harris 1984; Franklin and Forman 1987; Van Dorp and Opdam 1987), an important subtopic of landscape fragmentation.

Studying the relationships between structural and functional consequences of landscape fragmentation offers insight into the more general question of how landscape patterns and processes are correlated (Forman and Godron 1986; Turner 1989; Turner and Gardner 1991). In particular, the comparison of anthropogenic and geogenic fragmentation effects and

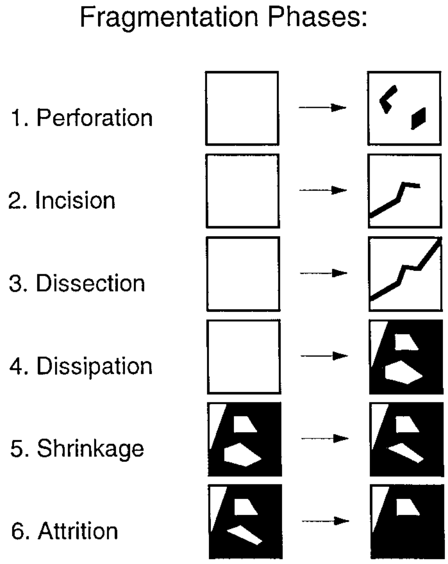


Figure 1. Phases of the fragmentation process, distinguished according to geometric characteristics (modified and extended after Forman 1995, p. 407, Figure 12.1).

of their spatial and temporal scales provides fruitful research opportunities.

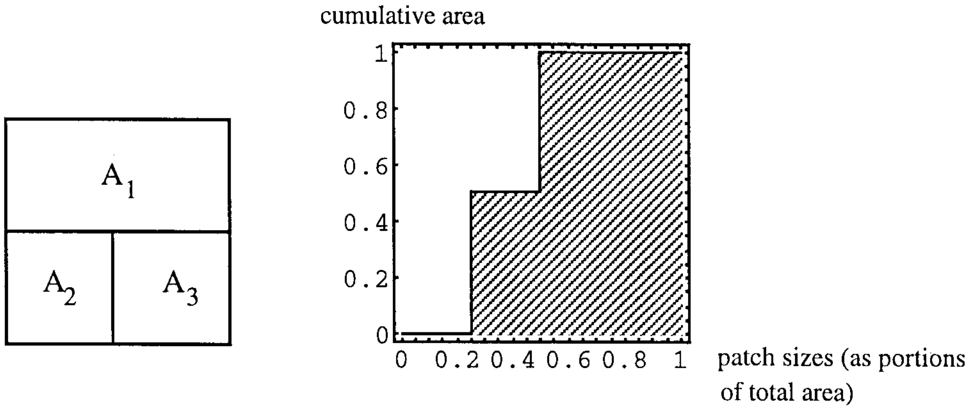
During the last twenty years, many landscape indices have been introduced for different purposes, e.g., dominance, diversity, contagion, and fractal dimension (O'Neill et al. 1988; Turner 1989; Turner and Gardner 1991; McGarigal and Marks 1995; Haines-Young and Chopping 1996). However, few of these are geared specifically to landscape fragmentation. Some measures do reflect major aspects of landscape fragmentation. Most of them include further aspects of landscape spatial pattern but their sensitivities to the wealth of different aspects of heterogeneity have not yet been analyzed and compared systematically (Riitters et al. 1995; Gustafson 1998). In order to achieve more specific measures, it is necessary to detail the requirements of fragmentation measures and to establish productive reliability criteria. The purpose of this paper is to introduce three quantitative measures that characterize landscape fragmentation in a geometric perspective and to propose nine suitability criteria. It discusses the properties of the new measures in systematic comparison with five other landscape fragmentation indices found in pertinent literature in order to reveal their strengths and limitations.

Geometric description of landscape fragmentation

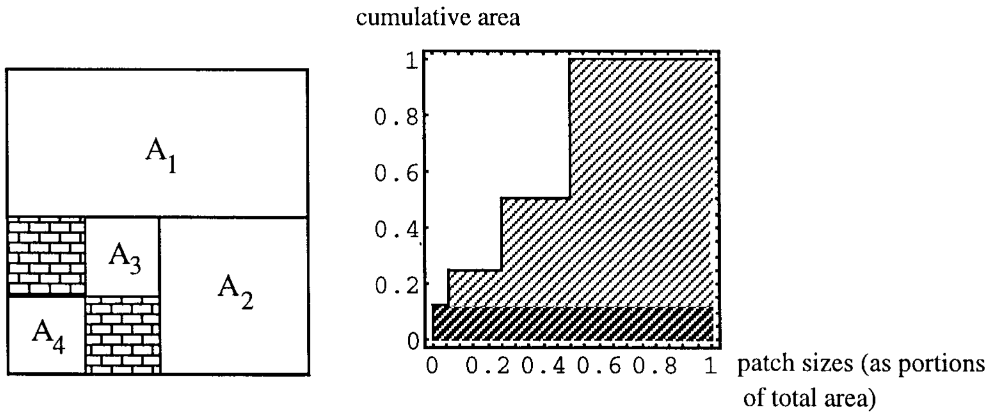
Six steps of landscape fragmentation can be distinguished (Figure 1) and can be recognized as phases in the change of real landscapes (Forman 1995, p. 407f). In reality, the phases are not strictly separated from each other since several of them take place simultaneously; however, a dominant phase can often be identified.

These depictions distinguish only between two types of areas. Their application to a landscape includes a decision about which landscape elements are assessed as fragmenting, and depends on the system property of interest (Li and Reynolds 1995, Gustafson 1998). Examples are the distinction between habitat and uninhabitable area (depending on the animal of interest) or between forested and non-forested area. The dissipation phase (4) can be represented as a combination of dissection (3) and shrinkage (5). For this reason, the notation here is different from Forman (1995). He uses 'fragmentation' to refer to only the dissipation phase (4). In this paper, however, 'fragmentation' shall be used as a more comprehensive notion for all six phases. From a purely geometric point of view, the dissipation phase has no separate meaning relative to the phases (3) and (5). Nevertheless is it considered as an extra phase because of its metaphorical suitability and because of its different genesis compared to phases (3) and (5) in real landscapes, i.e., when dissection and shrinkage take place at once and cannot be regarded as separate processes. Further, an *incision* phase is distinguished from the dissection phase (extending Forman's original concept of five phases).

According to the particular phases, different quantitative measures are appropriate to describe the changes of landscape pattern and to relate them to ecological functions. Furthermore, the distinction of these phases is useful in characterizing the sensitivity of a quantitative measure of fragmentation (see below). The main objectives of a quantitative description of landscape fragmentation are to analyse and to document fragmentation trends over time, to compare different regions relative to their fragmentation and its consequences, and to assess the measures that are taken as compensation for the construction of new facilities. It would be desirable to have a measure that behaves consistently in all six fragmentation phases because in real landscapes, the phases often cannot be separated from one another. Otherwise, some phases would seem to be compensated by others, even though



Example (a): area configuration and cumulative area distribution function; $D = 62.5\%$.



Example (b): area configuration and cumulative area distribution function.

Outcomes for (b): degree of landscape division $D = 68\%$, splitting index $S = 3.1$, effective mesh size $m = 5.1\ \text{km}^2$;

(auxiliary measures: degree of coherence $C = 32\%$, splitting density $s = 0.2 \frac{1}{\text{km}^2}$, net product $N = 81.6\ \text{km}^4$).

Figure 2. Two examples for determining D, S, and m. (a) Area configuration and diagram of the cumulative area distribution function for the example $\Phi = \{A_1 = 2\ \text{km}^2, A_2 = 1\ \text{km}^2, A_3 = 1\ \text{km}^2\}$, $A_t = 4\ \text{km}^2$. The degree of landscape division (D) is represented by the shaded area below the curve. (b) Area configuration and diagram of the cumulative area distribution function for the example $\Phi = \{A_1 = 8\ \text{km}^2, A_2 = 4\ \text{km}^2, A_3 = 1\ \text{km}^2, A_4 = 1\ \text{km}^2\}$, $A_t = 16\ \text{km}^2$. In the area configuration, settlement areas are represented by a brick-like gridwork. D is represented as the area below the curve (hatched); the 'pedestal' caused by the settlements is emphasized by dark shading.

all phases contribute to fragmentation. Fragmentation measures should:

- increase monotonously when new sites are converted into intensively used areas, e.g., into settlement areas and roads;
- have an intuitive interpretation;
- not be too sensitive to the omission or addition of very small residual areas;
- not require much data input;
- be as simple as possible from a mathematical point of view.

Definition of new fragmentation measures

The three new fragmentation measures degree of landscape division (D), splitting index (S), and effective mesh size (m), are based on the ability of two animals – placed in different areas somewhere in a region – to find each other within the landscape. This is equivalent to the probability that two randomly chosen places in a region will be found in the same undissected area. For the sake of clarity, the measures are introduced via three auxiliary measures: coherence (C), splitting density (s), and net product (N). The introduction of the measures is motivated by the following reasons:

- The possibility of two individuals to meet is a precondition for the survival of a population. It takes into account the size of undissected areas and the accessibility of inhabitable places.
- The size of undissected areas and the accessibility of these areas are two of the most important factors influencing extinction. They are inversely correlated with, for example, the isolation of subhabitats and the separation of the subpopulations of a metapopulation.
- It is unnecessary to consider more than two individuals when pursuing structural information; less than two is obviously insufficient. Therefore, considering two individuals involves the least possible expenditure of calculation.

Depending on the system property of interest, i.e., the decision which landscape elements are assessed as fragmenting, a binary categorical map is prepared. The remaining areas are defined as patches. In the following definitions, the set of the remaining n patches of a landscape is denoted by $\Phi = \{A_i | i = 1, \ldots, n\}$. The total area of the region is given by $A_t \geq \sum_{i=1}^{n} A_i$. Φ can be depicted as an area distribution function (expressing the number of patches in Φ as a function of patch size).

(1) Degree of landscape division D (or DIVI) and degree of coherence C (first auxiliary quantity, COHE)

The degree of coherence is defined as the probability that two animals placed in different areas somewhere in the region of investigation might find each other:

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

with n = number of patches; A_i = sizes of the n patches ($i = 1, \ldots, n$); A_t = total area of the region.

C can be represented graphically as the area above the line in the diagram of the cumulative area distribution function (see example in Figure 2a). Alternatively, C can be understood to be the probability that two animals, which have been able to move throughout the whole region before the fragmentation processes took place, will be found in the same partial area when the network of dissecting lines and areas is placed over the region.

The degree of landscape division (D) is defined as the probability that two randomly chosen places in the landscape under investigation are *not* situated in the same undissected area:

$$D = 1 - \sum_{i=1}^{n} \left(\frac{A_i}{A_t} \right)^2.$$

Graphically, D is represented as the area *below* the curve in the diagram of the cumulative area distribution function (Figure 2b).

(2) Splitting index S (SPLI)

The splitting index (S) is defined as the number of patches one gets when dividing the total region into parts of equal size in such a way that this new configuration Φ' leads to the same degree of landscape division (D) as was obtained for Φ. A simple calculation results in:

$$S = \frac{A_t^2}{\sum_{n=1}^{n} A_i^2}.$$

If all patches of an area distribution Φ have the same size, then $\Phi' = \Phi$ and $S = n$. S can be interpreted to be the 'effective mesh number' of a network Φ' with a constant mesh size dividing the region into S patches which all have the size A_t/S.

(3) Effective mesh size m (MSIZ)

The effective mesh size (m) denotes the size of the areas when the region under investigation is divided into S areas (each of the same size A_t/S) with the same degree of landscape division as for Φ:

$$m = \frac{A_t}{S} = \frac{1}{A_t} \sum_{i=1}^{n} A_i^2.$$

(4) Splitting density s (second auxiliary quantity, SDEN)

When a landscape is characterized by the splitting index (S) then the number of 'meshes' per unit area is given by the splitting density:

$$s = \frac{S}{A_t} = \frac{A_t}{\sum_{i=1}^{n} A_i^2} = \frac{1}{m}.$$

(5) Net product N (third auxiliary quantity, NPRO)

The net product (N) is defined as the product of the effective mesh size, m, and the total area of the region:

$$N = m \cdot A_t = \sum_{i=1}^{n} A_i^2.$$

This quantity is the extensive counterpart of the effective mesh size (m) (see below).

Mathematically speaking, these measures are different conversions of the second moment of a distribution function of a stochastic variable corresponding to the area distribution function, i.e., of $\sum(A_i/A_t)^2$. Generally, a distribution function is determined definitely by all its moments (Kreyszig 1979, p. 96). The fragmentation of a region is most simply expressed via the second moment of the distribution function. Thus, the new measures contain mainly the same information, but have different interpretations and different mathematical properties. A particular advantage of the quantity $\sum(A_i/A_t)^2$ is its insensitivity to the omission or addition of very small residual areas, a well-known feature of higher-order terms. In practice, this makes the results more reproducible as different authors do not always use the same lower limit of patch size in their quantitative recordings of an area distribution. This advantage distinguishes the measures introduced here from many other fragmentation measures, especially from the number of patches (n) and the average patch size ($\bar{A}$), which are sensitive to all patches independently of their sizes.

The area occupied by settlements and traffic lines is graphically represented in the cumulative area distribution diagram as a 'pedestal' (Figure 2b). With regard to the definition of D, the pedestal can be understood in the following way: when one (or both) of the animals placed somewhere in the region is located in a settlement area, it is assumed the animal will perish and the probability of meeting is set at zero.

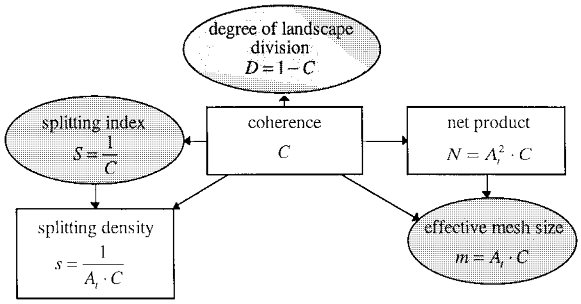


Figure 3. The structure of the relationships between the three fragmentation measures D, S, and m, (shaded), and the corresponding auxiliary quantities C, s, and N (white boxes).

When investigating the fragmentation of a region for different times with these measures, A_t should be the total area of the region and not the sum of the undissected areas. Otherwise, an increasing fragmentation due to shrinkage or attrition might not be reflected in an increasing value of D or S. However, it may also be interesting to calculate the measures in relation to the sum of undissected areas $A_{\text{sum}} = \sum_{i=1}^{n} A_i$ instead of A_t. (The mathematical characteristics discussed in the following hold true in both cases.)

Table 1 gives a synopsis of the mathematical characteristics of the three fragmentation measures and the three auxiliary quantities. The relationships between the measures are depicted in Figure 3.

The following characteristics are simple mathematical properties (cf., Chandler 1987, pp. 22–25) transferred to landscape pattern indices with interesting consequences for the use of the measures. Being *intensive* means remaining constant when the analysed region is being enlarged but keeping its structure. This property is a precondition for the interpretation of an index as quantifying an *intrinsic* feature. If the index increases by the same factor the region is multiplied by, it is called *extensive*. In other words, a landscape index, say F, is called intensive if $F(\lambda \cdot \Phi) = F(\Phi)$ and it is called extensive if $F(\lambda \cdot \Phi) = \lambda \cdot F(\Phi)$ (for all area configurations Φ and all $\lambda \in N$ with $\lambda \cdot \Phi$ defined as the multiplication of the region represented by Φ in the same spatial arrangement of patches, e.g., for $\Phi = \{1 \text{ ha}, 4 \text{ ha}, 5 \text{ ha}\}$ a multiplication by $\lambda = 2$ results in $2\Phi = \{1 \text{ ha}, 1 \text{ ha}, 4 \text{ ha}, 4 \text{ ha}, 5 \text{ ha}, 5 \text{ ha}\}$, etc.). To an extensive quantity, one can always find a corresponding intensive quantity by dividing by A_t (and *vice versa*). This constitutes the relationship between the splitting index (S) and the splitting density

Table 1. Synopsis of the three fragmentation measures D, S, and m introduced in this paper and some of their mathematical properties (homogeneity, additivity). To each measure, the corresponding auxiliary measure is added. (n = number of patches, A_i = sizes of the patches ($i = 1, \ldots, n$), A_t = total area of the region. Note: The measures can be related to $A_{\text{sum}} = \sum_{i=1}^{n} A_i$ instead of A_t, as determining the road density with respect to A_t or A_{sum})

Fragmentation measure	Formula	Homogeneity			Additivity	
		Extensive	Intensive	Neither extensive nor intensive	Directly additive	Area-proportionately additive
Effective mesh size	$m = \frac{1}{A_t} \sum_{i=1}^{n} A_i^2$		×			×
Net product	$N = \sum_{i=1}^{n} A_i^2$	×			×	
Splitting index (effective mesh number)	$S = \frac{A_t^2}{\sum_{i=1}^{n} A_i^2}$	×				
Splitting density	$s = \frac{A_t}{\sum_{i=1}^{n} A_i^2}$		×			
Degree of landscape division	$D = 1 - \sum_{i=1}^{n} \left(\frac{A_i}{A_t}\right)^2$			×		
Coherence	$C = \sum_{i=1}^{n} \left(\frac{A_i}{A_t}\right)^2$			×		

(s). The extensive quantity corresponding to m is the net product (N).

The most important feature of the new measures is that the effective mesh size (m) is area-proportionately additive, i.e., m characterizes the fragmentation of a region independently of its size and can be calculated for the combination of two or more regions from the effective mesh sizes of these regions in the same way temperature or concentration of a liquid is determined: When two liquids are mixed, the concentration of the mixture becomes

$$c = \frac{V_1}{V_1 + V_2} c_1 + \frac{V_2}{V_1 + V_2} c_2,$$

with V_j and c_j denoting the volumes and concentrations. The effective mesh size of the combination of two regions is determined analogously (Appendix A).

'Area-proportionately additive' means more than 'intensive': this mathematical characteristic is the most straightforward counterpart of what one intuitively understands as an intrinsic property. It coincides with the most intuitive expectation for the value of the combination of regions or of parts of a region: each part contributes proportionally to its size – even if each part has a different structure (as an example, cf., case studies in a separate paper). For example, the effective mesh size of the combination of two regions which have the same total area, but are dissected differently, is given by the mean value $m = \frac{1}{2}(m_1 + m_2)$. This characteristic makes the effective mesh size particularly helpful

- in comparing the fragmentation of regions of different sizes;
- in assessing the influence of parts of a region to the fragmentation of the total region when the fragmentation in some parts of the region are somehow changed;
- in assessing the fragmentation of a combination of several regions of different sizes.

The other measures defined above (degree of landscape division, splitting index, and the auxiliary measures) are *not* area-proportionately additive. In the literature, no area-proportionately additive measure of fragmentation is known, apart from some very simple measures (like road density, l) which do not reflect important structural differences (see next section).

The characteristics of being extensive or intensive, additive or area-proportionately additive, are interrelated: Every additive quantity is extensive, every area-proportionately additive quantity is intensive. The reverse generally does not hold. According to thermodynamics, for example, entropy is a quantity which is extensive but not additive (Straumann 1986, p. 38). Average patch size ($\bar{A}$) is an example of an intensive measure which is *not* area-proportionately additive.

Comparison with other fragmentation measures

Frequently used as fragmentation measures are the number of undissected areas (n), the average size of areas, $\bar{A} = A/n$, and the density of roads, $l = \sum L_j/A$ (L_j = lengths of the roads, A = total area of the region, A_t, or sum of patches, A_{sum}). Furthermore, the literature includes Bowen's landscape dissection index (LDI) (Bowen and Burgess 1981) and the relative partitioning index (PI_{rel}) proposed by the German Federal Statistical Office (Deggau et al. 1992; Krack-Roberg et al. 1995).

Landscape dissection index LDI

The landscape dissection index (LDI) is defined by (Bowen and Burgess 1981):

$$LDI = \frac{\sum_{i=1}^{n} P_i}{2\sqrt{\pi A_t \sum_{i=1}^{n} A_i}},$$

with P_i = perimeters of the n patches, A_i = sizes of the patches, A_t = total size of the region. The definition of LDI is motivated by the patch index of island shape for an individual forest island, $IS = P/(2\sqrt{\pi A})$, where P is the perimeter and A is the area of the island (Wetzel 1975, p. 31; Patton 1975; Game 1980).

LDI is intensive, i.e., it stays constant when a region with a certain landscape pattern is multiplied, because $\sum P_i$, $\sum A_i$, and A_t are additive quantities. However, LDI is not an area-proportionately additive measure (see Appendix A). This result is reasonable as $\sum P_i$, $\sum A_i$, and A_t are additive, so that LDI (nearly the quotient of two additive quantities) is nearly area-proportionately additive with respect to A_t and with respect to $\sum A_i$ (and is in fact area-proportionately additive to them when $\sum A_i = A_t$), though not always, since A_t and $\sum A_i$ are usually different.

Relative partitioning index PI_{rel}

The relative partitioning index (PI_{rel}) is defined via the cumulative distribution functions of the patches for two landscape patterns $\mathcal{A}$ and $\mathcal{B}$. The relative dissection of $\mathcal{A}$ with respect to $\mathcal{B}$, $PI_{\text{rel}}(\mathcal{A}, \mathcal{B})$, is given by the Gini coefficient of the Lorenz line in the combined diagram, i.e., the quotient of the area between the Lorenz line and the diagonal and half of the total diagram area. (Figure 6c in Appendix A; for details see Deggau et al. 1992.) This definition was motivated by the objective of analysing changes in the pattern of a landscape over time.

When a region is multiplied, i.e., extended while keeping its spatial structure, PI_{rel} remains unchanged, but is not an area-proportionately additive measure. The main problem with PI_{rel} is that it often becomes 100% and, hence, no further differentiations are possible from that point on (Appendix A).

Formally, the degree of landscape division (D) shows some similarity to Simpson's diversity index ($SIDI$) as defined by McGarigal and Marks (1995):

$$SIDI = 1 - \sum_{k=1}^{l} p_k^2,$$

where l = number of all potentially different patch types (classes) and p_k = proportional abundance of patch type k. If only one patch type occurs then $SIDI$ equals zero. It reaches its maximum value $1 - l^{-1}$ if all patch types have the same portion of the region. D differs from $SIDI$ in two points:

- The sum does not run over patch *types* but over the number of patches. This means that the area distribution of the patches is considered in D.
- D distinguishes between two types of areas: suitable and not suitable (or barrier). In contrast to this, $SIDI$ does not respect the differences between patch types, e.g., between forests and parking places. As a consequence, $SIDI$ is not suitable to be used as a fragmentation index because it *decreases* when the abundance of settlement areas exceeds $> l^{-1}$.

Further measures used for quantifying fragmentation are proximity, lacunarity, and contagion (McGarigal and Marks 1995; Plotnick et al. 1993; Riitters et al. 1995, 1996; Haines-Young and Chopping 1996; Gustafson 1998). Hargis et al. (1998) further include nearest neighbor distance and fractal dimension. These measures are not investigated here since they contain more aspects of spatial heterogeneity than fragmentation and, hence, are more general measures of landscape texture. Additionally, they are mathematically more complicated. For example, in determining contagion, difficulties arise in representing roads as barriers (because contagion is designed for raster images), and the results are strongly affected by the grain size or resolution of the image (McGarigal and Marks 1995, p. 53); proximity involves a neighborhood radius (whose influence would have to be investigated; McGarigal and Marks 1995) and is very sensitive to small distances (this leads to difficulties when narrow barriers such as roads are considered). These influences would have to be studied in more detail beyond this study. In order to design simple and reliable measures of fragmentation it is possible to advance without as much mathematical input. The mathematical simplicity of the measures introduced in this paper promotes their likelihood that they will be widely used in practice.

Illustration and comparison of the indices by use of two dissection pattern series

The following model of two pattern series illustrates how differently the measures react to structural characteristics of a pattern and how sensitive they are to the differences between the two pattern series. The pattern series are constructed by the addition of roads to a square, 10 km × 10 km. A road length of 10 km is added in each step until the total area is divided into 20 × 20, or 400 patches. In series (a), the region is divided into patches of equal size. In series (b), the distances between the roads added is kept constant at 500 m resulting in differing patch sizes (Figure 4). (The number of patches and their relative positions are the same in both series).

In this simple model, it can be seen that some measures distinguish between (a) and (b), and some do not. This distinguishing ability of an index is a necessary condition for qualifying as a structural measure. Furthermore, one can discern in this model how strong and in which direction the measures reflect those structural differences (Figure 5).

Patch number (n), average patch size ($\bar{A}$), and landscape dissection index (LDI) cannot distinguish between (a) and (b) whereas splitting index (S), degree of landscape division (D), and effective mesh size (m) reflect structural differences between the two pattern series. The relative partitioning index (PI_{rel}) represents structural differences between the k-th configuration of (a) and (b) and of the last pattern (i.e., $k = 39$) relative to $(\text{b})_k$. (The partitioning index for the last pattern relative to $(\text{a})_k$ is 100% for all k.). The indices can be calculated in formulas (Appendix B).

Discussion

Reaction to different fragmentation phases

As shown in Table 2, some measures react to all six fragmentation phases in the same direction (i.e., ever increasing or decreasing), some react differently to different phases (i.e., increasing reaction to some phases and decreasing reaction to others), and some vary in their reaction even to processes of the *same* fragmentation phase.

For example, the relative partitioning index (PI_{rel}) and the landscape dissection index (LDI) vary in their reaction to the *shrinkage phase*. Sometimes they increase, sometimes they remain unchanged, sometimes they decrease (Appendix A). The relative partitioning index (PI_{rel}) shows a somewhat confusing and contra-intuitive feature: if two shrinkage processes with *increasing* PI_{rel} are performed successively, then their combination sometimes leads to a *negative* value of PI_{rel}, indicating a decrease in fragmentation (Appendix A).

Consequently, LDI and PI_{rel} are not suitable as measures of shrinkage, nor are they sutitable for real landscapes when shrinkage is involved. An increase of fragmentation, e.g., due to dissection, might be compensated as an effect of a shrinkage process. In this case, a measure should be used that reacts in the same way to dissection and shrinkage – as does the average area ($\bar{A}$) – or that does not react to shrinkage, a measure such as the number of patches (n). These two measures ($\bar{A}$ and n), however, are not suitable if the phase of attrition is involved since they react to attrition in an opposite manner.

The findings noted in Table 2 show that LDI and PI_{rel} do not correspond with fragmentation. Only in the case of dissection, is the relative partitioning index (PI_{rel}) a reliable fragmentation measure. It is not suitable when perforation, dissipation, shrinkage, or attrition occur. LDI is an expression of the proportion of edge to area in a landscape, but it is not strictly correlated to the fragmentation of a landscape. It is necessary to consider LDI always in connection with the sum of patch sizes $\sum A_i$ because one has to know whether $\sum A_i$ has increased or not in order to interpret changes of LDI as a reduction or an enhancement of landscape fragmentation. It is appropriate for a quantification of landscape changes when only perforation,

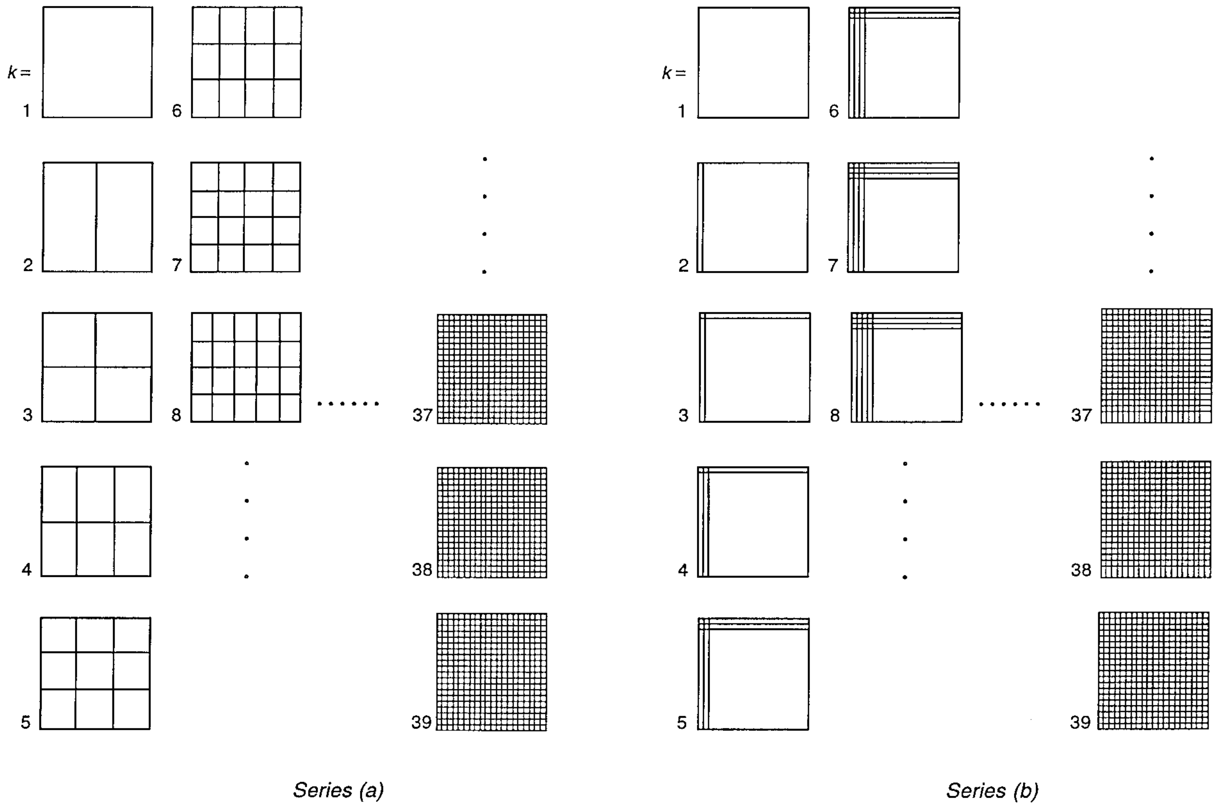


Figure 4. The two pattern series (a) and (b) compare the sensitivity of the measures to structural differences. The variable k counts the steps, beginning with $k = 1$ and ending with $k = 39$.

Table 2. Sensitivity of the measures to the six fragmentation processes. The degree of landscape division (D), the splitting index (S), the effective mesh size (m), and the road density (l and l^*) are the only ones that are reliably increasing (resp. decreasing) to an increase in fragmentation. (D = degree of landscape division, S = splitting index, m = effective mesh size, PI_{rel} = relative partitioning index, LDI = landscape dissection index, n = number of patches, $\bar{A}$ = average patch size, l = road density in relation to total area, l^* = road density in relation to the sum of patch areas; $-$ = measure reacts to this process by a decrease of its value, o = measure does not react to this process, $+$ = increasing reaction to this process, $+/o/-$ = sometimes decreasing, sometimes increasing, and sometimes no reaction to this process)

Fragmentation phase	Measures								
	D	S	m	PI_{rel}	LDI	n	$\bar{A}$	l	(l^*)
Perforation	+	+	−	+/o/−	+	o	−	o	(+)
Incision	o	o	o	o	+	o	o	+	(+)
Dissection	+	+	−	+	+	+	−	+	(+)
Dissipation	+	+	−	+/o/−	+/o/−	+	−	+	(+)
Shrinkage	+	+	−	+/o/−	+/o/−	o	−	o	(+)
Attrition	+	+	−	−	+/o/−	−	+/o/−	o	(+)

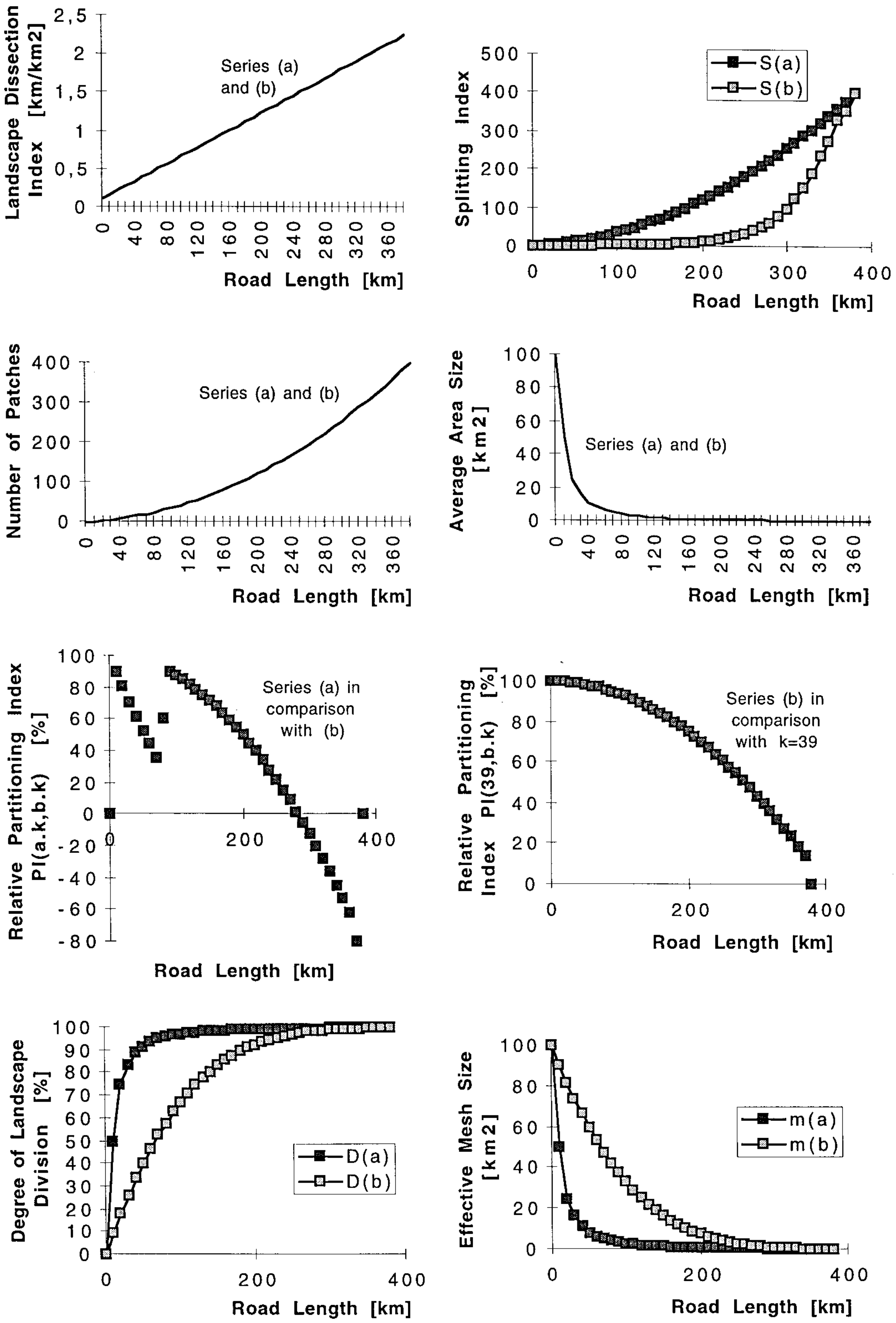


Figure 5. Results for the two pattern series (a) and (b) from Figure 4. LDI, S, n, $\bar{A}$, PI_{rel}, D, and m are shown as functions of road length.

incision, and dissection are involved, but it is not a reliable measure for all fragmentation phases.

The road density increases when new roads are built or when the sum of patch areas decreases (assuming l^* is defined relative to $\sum A_i$ instead of to A_t). Roads running through settlements also have to be considered by l. Otherwise, l would indicate a reduction of fragmentation when the settlements grew.

The comparison of the measures in Table 2 demonstrates that different measures are suitable for different phases of fragmentation. In real landscapes, the fragmentation phases overlap (Forman 1995, p. 408). Therefore, the measures which react in the same direction to all phases are most suitable, i.e., degree of landscape division (D), splitting index (S), road density (l or l^*), and effective mesh size (m).

Suitability criteria for fragmentation measures

Table 3 comprises nine suitability criteria for assessing and comparing the eight measures. The first three criteria are best met by the three simplest measures: number of patches (n), average area ($\bar{A}$), and road density (l). The new measures, degree of division (D), splitting index (S), and effective mesh size (m) are not as intuitively imaginative as n, $\bar{A}$, and l, but more intuitive than the relative partitioning index (PI_{rel}) and the landscape dissection index (LDI).

The next three criteria concern the correlation of the measures with the processes of fragmentation. From a practical point of view, the number of patches (n) and the average patch size ($\bar{A}$) are far too sensitive to the inclusion or omission of very small patches. Only the degree of division (D), the splitting index (S), the effective mesh size (m), and the road density (l) fulfil the next criterion, i.e., monotony of reactions to different fragmentation phases. The subsequent criterion concerns the ability to reflect structural differences between the pattern series in Figure 4. Such differences can be detected by the first four measures, D, S, m, and PI_{rel}, but the other four measures are insensitive to these differences. Thus, they do not qualify as structural measures.

The following two criteria refer to mathematical properties that are relevant for the applicability of the measures. Intensity of a measure (i.e., constancy of its value when the investigated region is multiplied) is a necessary precondition when comparing regions with differing total areas. D, S, and n are not intensive; they are suited only for the comparison of regions with the same total area or in order to investigate the fragmentation development of a region over time. Being area-proportionately additive is fulfilled by the effective mesh size (m) and the road density (l). Thus, m is the only measure that is both area-proportionately additive and reflects structural differences. In conclusion, m combines the advantages of intrinsic and structural measures and fulfils more criteria than any other fragmentation measure.

The last criterion, inquiring to what extent a measure can be interpreted as a measure of fragmentation, comprises the criteria (1), (5), and (6). It represents the main result of this study. According to the requirements considered, the three new measures are unreservedly appropriate as fragmentation measures, while the suitability of the other five measures is more or less severely limited.

Utility of the new fragmentation measures

The new measures D, S, and m can be applied on various scales and to different habitat types. For example, there are, at least, three ways to apply the measures:

(A) to forests only;
(B) to all areas that are not settlements or traffic areas;
(C) to all areas that are not settlements, traffic areas, or intensively used agricultural areas.

In addition to D, S, and m, further fragmentation measures that take into account differences of habitat quality and the relative position of the patches should be developed (cf., proximity index; McGarigal and Marks 1995). As a contribution to this objective, a topology-sensitive extension of the measures D, S, and m will be presented in a subsequent paper. Patch quality could be included by multiplying the patch sizes (A_i) by corresponding factors, e.g., if the capacity of a habitat is reduced or enhanced by a certain factor. Further extensions of the measures could include the degree of landscape connectivity according to specific strategies of animal dispersal (cf., Taylor et al. 1993).

The measures discussed in this study – and other landscape indices – are useful for:

- documentation of landscape development and validating observations (especially for slow changes over long periods of time);
- spatially differentiated assessments of the fragmentation of a region and its parts and for the comparison of different regions;
- a systematic search for relationships between structural properties, landscape functions, and the direction of landscape changes;

Table 3. Results of comparing the measures with respect to nine suitability criteria ($-$ = not fulfilled, * = slightly fulfilled, ** = satisfying or good, *** = very good). (D = degree of landscape division, S = splitting index, m = effective mesh size, PI_{rel} = relative partitioning index, LDI = landscape dissection index, n = number of patches, $\bar{A}$ = average patch size, l = road density in relation to total area, l^* = road density in relation to the sum of patch areas)

Suitability criteria	Measures							
	D	S	m	PI_{rel}	LDI	n	$\bar{A}$	l
1. Intuitive interpretation	**	**	**	*	*	***	***	***
2. Mathematical simplicity	**	**	**	*	**	***	***	***
3. Modest data requirements	***	***	***	**	**	***	***	***
4. Low sensitivity to small patches	***	***	***	***	**	–	–	***
5. Monotonous reaction to different fragmentation phases	***	***	***	–	–	–	–	**
6. Detection of structural differences[a]	yes	yes	yes	yes	no	no	no	no
7. Mathematical homogeneity (i.e., intensive or extensive measure)	no	extens.	intens.	intens.	intens.	extens.	intens.	intens.
8. Additivity	no	no	area-proportionately additive	no	no	additive	no	area-proportionately additive
9. Interpretation as a measure of fragmentation	***	***	***	**	*	*	*	**

[a] E.g., between series (a) and (b) in Figure 4.

- a test of hypotheses about the existence and location or type of critical thresholds in spatial pattern (Turner and Gardner 1991, p. 5);
- sharpening the conception of fragmentation by the discussion of quantitative expressions.

By use of these measures, it is feasible to analyse alterations in traffic networks and to find out which traffic pattern leads to a minimum of landscape fragmentation. For example, the consequences of different design principles, such as the bundling of roads, could be researched (Müller et al. 1998).

Moreover, such measures seem to be suitable as proxy measures – as proposed by Schmidt-Bleek (1993) and Berg and Scheringer (1994) – for an assessment of environmental impacts by aggregating several different impact factors. The need for proxy measures in landscape ecology, as well as for environmental risk assessment has been emphasized in the reference literature (e.g., Turner and Gardner 1991; Geoghegan et al. 1997).

Conclusions

The measures discussed in this study show different sensitivities to the different fragmentation processes (perforation, incision, dissection, etc.). Consequently, one has to apply suitable measures in correspondence with the respective fragmentation phase, e.g., Bowen's landscape dissection index (LDI) for the incision phase, the relative partitioning index (PI_{rel}) for the dissection phase, etc. (cf., Table 2). The new measures (D, S, and m) have proved to be suitable for all fragmentation phases. The comparison with five other measures from the literature (McGarigal and Marks 1995; Bowen and Burgess 1981; Krack-Roberg et al. 1995) has revealed that the proposed measures lead to improvements with respect to the following suitability criteria (cf., Table 3):

- low sensitivity to very small patches;
- monotony of their reaction to different fragmentation phases (Forman 1995);
- ability to distinguish spatial patterns;
- mathematical simplicity.

For this reason, the new measures can be interpreted as measures of fragmentation more conclusively than the older ones. In particular, the effective mesh size (m) is an appropriate fragmentation measure because of its mathematical characteristics and its intuitive interpretation. Expressed as a trenchant inference, one could conclude that the number of patches (n), the average patch size ($\bar{A}$), and the relative partitioning index (PI_{rel}) should be replaced by the effective mesh number (S), the effective mesh size (m), and the degree of landscape division (D):

$$n \rightarrow S,$$

$$\bar{A} \rightarrow m,$$

$$PI_{\mathrm{rel}} \rightarrow D.$$

In the case of incision, however, the road density (l) or the landscape dissection index (LDI) should also be applied.

The measures have been assessed systematically with respect to nine suitability criteria (intuitive interpretation, mathematical simplicity, data requirements, etc.). The results provide a first answer to the suggestion of Riitters et al. (1995, p. 33) to investigate the relative sensitivity of different but similar metrics to land use changes over time. They state that ‘the statistical and sampling details of most landscape metrics need to be better-known if the metrics are to be used effectively for environmental monitoring’.

Further development of landscape indices can benefit from the interplay of two contrary trends of *index differentiation* in order to distinguish between specific aspects of landscape structure on one side and *concentration* or reduction on the other. Selecting a few indices representing groups of correlated measures is sufficient for a rough characterization of landscape texture (Riitters et al. 1995), but for more detailed investigations one has to implement suitable measures geared to specific requirements (cf., Riitters et al. 1996).

Acknowledgements

I wish to thank M. Scheringer for his encouragement, for helpful comments on the manuscript, and for valuable discussions about the concept of environmental threat. I also thank K.C. Ewald, M. Ferry, E. Gustafson, P. Imsdahl, E. Jaeger, C. Lohmann, U. Müller-Herold, A.-K. Pantli, O. Renn and an anonymous reviewer for their constructive comments on the manuscript, J. Reidel for drawing my attention to significant literature, and D. Müller for fruitful discussions about landscape fragmentation and material fluxes in the research project *Synoikos* at the ETH Zürich. This work was supported by a doctoral grant from the ‘Studienstiftung des deutschen Volkes’.

Appendix A. Some characteristics of the effective mesh size (*m*), of the landscape dissection index (*LDI*), and of the relative partitioning index (*PI*$_{\mathbf{rel}}$)

Effective mesh size m

Let Φ_1 and Φ_2 be two area distributions $\Phi_1 = \{A_i^{(1)} | i = 1, \ldots, n_1\}$, $\Phi_2 = \{A_j^{(2)} | j = 1, \ldots, n_2\}$ with total areas $A_t^{(1)}$ and $A_2^{(2)}$. The effective mesh size (m) of the joint configuration $\Phi_1 \cup \Phi_2$ results in

$$\begin{aligned} m(\Phi_1 \cup \Phi_2) &= \frac{1}{A_t^{(1)} + A_t^{(2)}} \left(\sum_{i=1}^{n_1} \left(A_i^{(1)} \right)^2 + \right. \\ & \left. + \sum_{j=1}^{n_2} \left(A_j^{(2)} \right)^2 \right) \\ &= \frac{A_t^{(1)}}{A_t^{(1)} + A_t^{(2)}} \cdot m\,(\Phi_1) + \\ & + \frac{A_t^{(2)}}{A_t^{(1)} + A_t^{(2)}} \cdot m\,(\Phi_2)\,, \end{aligned}$$

i.e., m is an area-proportionately additive quantity.

Landscape dissection index LDI

The landscape dissection index (LDI) (Bowen and Burgess 1981) is not area-proportionately additive. This can be shown in the following way. If LDI was an area-proportionately additive quantity, the equation

$$LDI(\Phi_1 \cup \Phi_2) = \tfrac{A_t^{(1)}}{A_t^{(1)}+A_t^{(2)}} LDI(\Phi_1) + \\ + \tfrac{A_t^{(2)}}{A_t^{(1)}+A_t^{(2)}} LDI(\Phi_2)$$

would hold for all area distributions Φ_1 and Φ_2. In the following example (Figure 6a), this equation is not fulfilled: $\Phi_1 = \{1\ \mathrm{km}^2\}$, $A_t^{(1)} = 4\ \mathrm{km}^2$, $P_1 = 4$ km; $\Phi_2 = \{4\ \mathrm{km}^2\}$, $A_t^{(2)} = 4\ \mathrm{km}^2$, $P_2 = 8$ km. One gets

$$LDI(\Phi_1 \cup \Phi_2) < \frac{A_t^{(1)}}{A_t^{(1)} + A_t^{(2)}} LDI(\Phi_1) + \\ + \frac{A_t^{(2)}}{A_t^{(1)} + A_t^{(2)}} \mathrm{LDI}(\Phi_2).$$

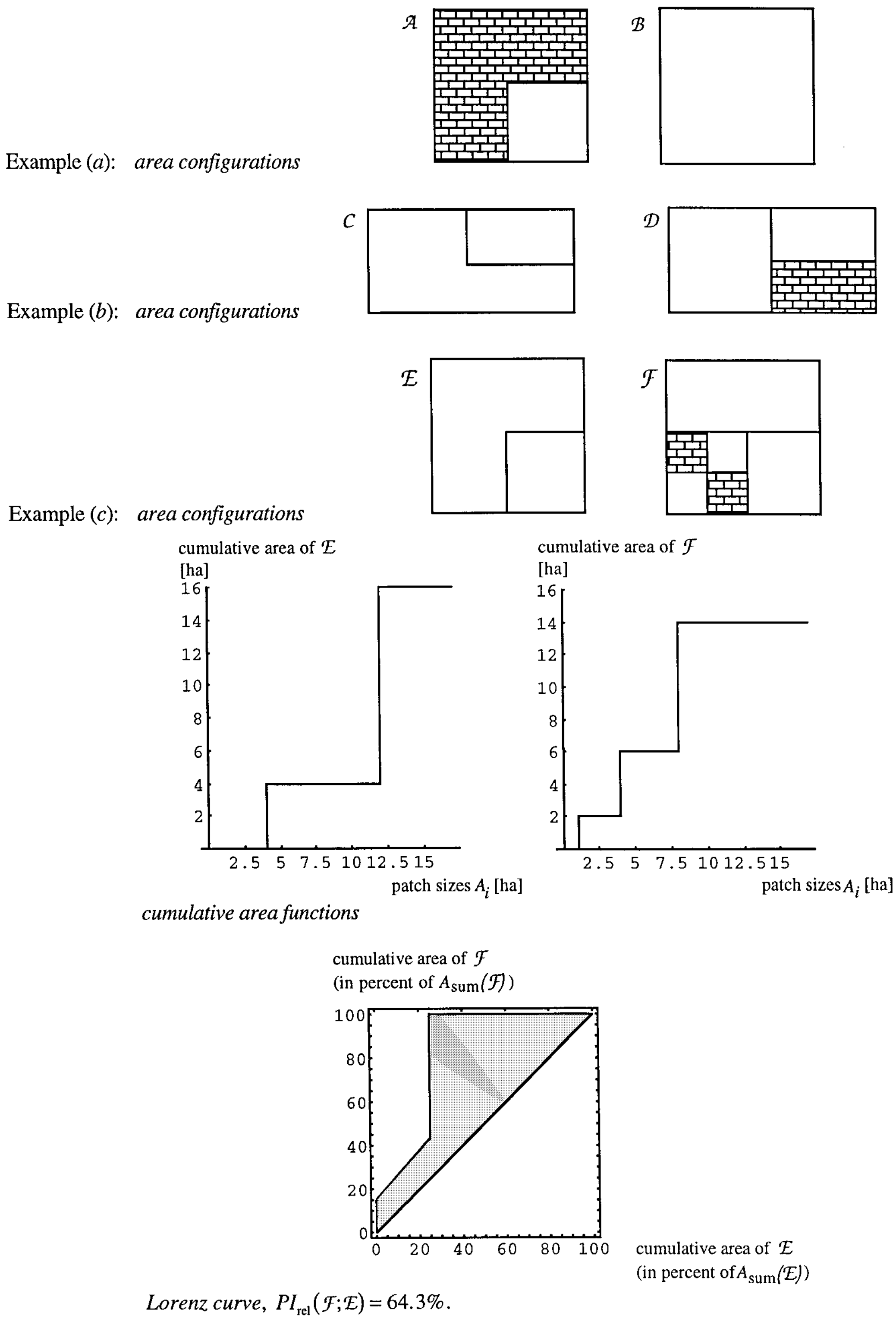


Figure 6. Examples illustrating the properties of the landscape dissection index (LDI) and of the relative partitioning index (PI_{rel}). (a) Example of the statement that LDI is not area-proportionately additive. (b) Example of a decreasing value of LDI in the shrinking phase. (c) Example of determining the relative partitioning index. PI_{rel} equals the area located between the Lorenz curve and the diagonal (shaded).

The landscape dissection index (LDI) does not react monotonously to the phase of shrinkage. This is illustrated by the following example which shows a decreasing value of LDI in the shrinkage phase (Figure 6b). Two configurations are compared: $\Phi_C = \{6\ \text{km}^2,\ 2\ \text{km}^2\}$, with $A_t^C = 8\ \text{km}^2$, $P_1^C = 12$ km, $P_2^C = 6$ km, and $\Phi_{\mathcal{D}} = \{4\ \text{km}^2,\ 2\ \text{km}^2\}$, with $A_t^{\mathcal{D}} = 8\ \text{km}^2$, $P_1^{\mathcal{D}} = 8$ km, $P_2^{\mathcal{D}} = 6$ km. One gets

$$LDI_C = \frac{13.5}{12\sqrt{\pi}\text{km}} \quad \text{and}$$

$$LDI_{\mathcal{D}} = \frac{7 \cdot \sqrt{3}}{12\sqrt{\pi}\text{km}} < LDI_C.$$

Relative partitioning index PI_{rel}

In order to show how to determine the relative partitioning index (PI_{rel}) (Deggau et al. 1992, p. 197f; Krack-Roberg et al. 1995), it is calculated for the following configuration (Figure 6c): $\Phi_{\mathcal{E}} = \{4\ \text{ha}, 12\ \text{ha}\}$, $A_t^{\mathcal{E}} = 16$ ha, $\Phi_{\mathcal{F}} = \{1\ \text{ha}, 1\ \text{ha}, 4\ \text{ha}, 8\ \text{ha}\}$, $A_t^{\mathcal{F}} = 16$ ha. One gets $PI_{\text{rel}} = 64.3\%$.

Two problems limit the performance of PI_{rel}. PI_{rel} frequently results in its maximum value (i.e., 100%). In particular, this is always the case when all areas of the first pattern are smaller than the smallest patch of the second pattern. For example, often it is not possible to distinguish between two configurations $\mathcal{B}$ and $\mathcal{C}$ (with different traffic networks) when PI_{rel} is calculated in relation to a configuration $\mathcal{A}$ (with a simpler reference network or without traffic network), although $\mathcal{C}$ may be considerably more fragmented than $\mathcal{B}$. Only the direct contrast $PI_{\text{rel}}(\mathcal{C}; \mathcal{B})$ reveals the difference. The problem that PI_{rel} becomes 100% occurs not only in model patterns, but also in reality. Examples are given in Krack-Roberg et al. (1995, p. 36) and Deggau et al. (1992, p. 202).

A second problem is its contra-intuitive behavior in the phase of shrinkage. Two shrinkage processes with increasing PI_{rel} performed successively sometimes lead to a decreasing value of PI_{rel}. This is the case in the following example. Three configurations, $\Phi_{\mathcal{A}}$, $\Phi_{\mathcal{B}}$, and $\Phi_{\mathcal{C}}$, are considered with
$\Phi_{\mathcal{A}} = \{3\ \text{km}^2, 2\ \text{km}^2, 2\ \text{km}^2, 1\ \text{km}^2, 1\ \text{km}^2\}$, $\Phi_{\mathcal{B}} = \{3\ \text{km}^2, 1\ \text{km}^2, 1\ \text{km}^2, 0.5\ \text{km}^2, 0.5\ \text{km}^2\}$, and $\Phi_{\mathcal{C}} = \{3\ \text{km}^2, 0.5\ \text{km}^2, 0.5\ \text{km}^2, 0.5\ \text{km}^2, 0.5\ \text{km}^2\}$.

Pattern $\mathcal{B}$ results from $\mathcal{A}$ due to shrinkage of two patches, and $\mathcal{C}$ from $\mathcal{B}$ due to shrinkage. One finds that $PI_{\text{rel}}(\mathcal{B}; \mathcal{A}) = +9.3\%$ and $PI_{\text{rel}}(\mathcal{C}; \mathcal{B}) = +3.3\%$, indicating an increasing fragmentation; the dissection index of $\mathcal{C}$ relative to $\mathcal{A}$, however, turns out to be negative: $PI_{\text{rel}}(\mathcal{C}; \mathcal{A}) = -0.02\%$. This shows that PI_{rel} cannot be used as an index of fragmentation in the shrinkage phase.

Appendix B. Determining the fragmentation measures for the two pattern series

The indices can be calculated for the two pattern series (a) and (b) in Figure 4 as functions of the counter k (defined in Figure 4). One has:

number of patches:

$$n_a = n_b = n = \begin{cases} \left(\dfrac{k+1}{2}\right)^2 & \text{if } k \text{ is odd;} \\ \dfrac{k}{2} \cdot \left(\dfrac{k}{2} + 1\right) & \text{if } k \text{ is even;} \end{cases}$$

average area size:

$$\bar{A}_a = \bar{A}_b = \frac{100\ \text{km}^2}{n};$$

road density:

$$l_a = l_b = (k-1)/10\ \text{km};$$

landscape dissection index:

$$LDI_a = LDI_b = \frac{k+1}{10\sqrt{\pi}\text{km}};$$

degree of landscape coherence:

$$C_a = n^{-1};$$

$$C_b = \frac{1}{40^4} \begin{cases} 4(k-1)^2 + 4(k-1) \cdot (41-k)^2 + \\ \qquad (41-k)^4 \quad \text{if } k \text{ is odd;} \\ 4k(k-2) + 2k(42-k)^2 + 2(k-2) \cdot \\ \qquad (40-k)^2 + (40-k)^2 \cdot (42-k)^2 \\ \qquad \text{if } k \text{ is even;} \end{cases}$$

degree of landscape division:

$$D_a = 1 - \frac{1}{n}; \quad D_b = 1 - C_b;$$

splitting index:

$$S_a = n; \quad S_b = \frac{1}{C_b};$$

effective mesh size:

$$m_a = \frac{100\ \text{km}^2}{n}; \quad m_b = 100\ \text{km}^2 \cdot C_b.$$

The relative partitioning index (PI_{rel}) cannot be expressed as a function of k as simply as the other indices.

References

Berg, M. and Scheringer, M. 1994. Problems in environmental risk assessment and the need for proxy measures. Fresenius Env Bull 3: 487–492.

Bowen, G. W. and Burgess, R. L. 1981. A quantitative analysis of forest island pattern in selected Ohio landscapes. ORNL Environmental Sciences Division, Publication No. 1719, ORNL/TM-7759. Oak Ridge, TN, 111 pp.

Burgess, R. L. and Sharpe, D. M. (eds). 1981. Forest Island Dynamics in Man-Dominated Landscapes. Ecological Studies, Vol. 41, Springer-Verlag, New York, NY, 310 pp.

Chandler, D. 1987. Introduction to Modern Statistical Mechanics. Oxford University Press Inc., New York, NY, 274 pp.

Deggau, M., Krack, E., Radermacher, W., Schmid, B. and Stralla, H. (German Federal Statistical Office, Wiesbaden). 1992. Methodik der Auswertung von Daten zur realen Bodennutzung im Hinblick auf den Bodenschutz. Teilbeitrag zum Praxistest des Statistischen Informationssystems zur Bodennutzung (STABIS). Forschungsbericht 107 06 001/03 UBA-FB 92-084, edited by the German Federal Environmental Agency, Berlin, 292 pp.

Forman, R. T. T. and Godron, M. 1986. Landscape Ecology. John Wiley & Sons Inc., New York, NY, 620 pp.

Forman, R. T. T. 1995. Land Mosaics. The ecology of landscapes and regions. Cambridge University Press, Cambridge, 632 pp.

Franklin, J. F. and Forman, R. T. T. 1987. Creating landscape patterns by forest cutting: Ecological consequences and principles. Landscape Ecol 1: 5–18.

Geoghegan, J., Wainger, L. A. and Bockstael, N. E. 1997. Spatial landscape indices in a hedonic framework: an ecological economics analysis using GIS. Ecol Economics 23: 251–264.

Game, M. 1980. Best shape for nature reserves. Nature 287: 630–632.

Gustafson, E. J. 1998. Quantifying landscape spatial pattern: What is the state of the art? Ecosystems 1: 143–156.

Haber, W. 1993. Ökologische Grundlagen des Umweltschutzes. Economica Verlag, Bonn, 98 pp.

Haines-Young, R. and Chopping, M. 1996. Quantifying landscape structure: a review of landscape indices and their application to forested landscapes. Prog Phys Geography 20: 418–445.

Hargis, C. D., Bissonette, J. A. and David, J. L. 1998. The behavior of landscape metrics commonly used in the study of habitat fragmentation. Landscape Ecol 13: 167–186.

Harris, L. D. 1984. The Fragmented Forest: Island Biogeography Theory and the Presevation of Biotic Diversity. University of Chicago Press, Chicago, IL, 211 pp.

Krack-Roberg, E., Riege-Wcislo, W. and Wirthmann, A. 1995. UGR Materials. Concept of an accounting system for land use and land cover. Final report to the working group 'Physical Environmental Accounting', German Federal Statistical Office, Wiesbaden, 175 pp.

Kreyszig, E. 1979. Statistische Methoden und ihre Anwendungen. Vandenhoeck and Ruprecht, Göttingen [1]1965, [7]1979, 451 pp.

Li, H. and Reynolds, J. F. 1995. On definition and quantification of heterogeneity. Oikos 73: 280–284.

McGarigal, K. and Marks, B. J. 1995. FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure. General Technical Report PNW-GTR-351. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Portland, OR. 122 pp.

Müller, D., Perrochet, S., Faist, M. and Jaeger, J. 1998. Ernähren und Erholen mit knapper werdender Landschaft. *In* Netzstadt: Transdisziplinäre Methoden zum Umbau urbaner Systeme. Ergebnisse im Forschungsprojekt Synoikos. pp. 28–59. Edited by P. Baccini and F. Oswald. vdf Hochschulverlag an der ETH Zürich, Zürich.

O'Neill, R. V., Krummel, J. R., Gardner, R. H., Sugihara, G., Jackson, B., DeAngelis, D. L., Milne, B. T., Turner, M. G., Zygmunt, B., Christensen, S. W., Dale, V. H. and Graham, R. L. 1988. Indices of landscape pattern. Landscape Ecol 1: 153–162.

Patton, D. R. 1975. A diversity index for quantifying habitat 'edge'. Wildlife Society Bulletin 3: 171–173.

Plotnick, R. E., Gardner, R. H. and O'Neill, R. V. 1993. Lacunarity indices as measures of landscape texture. Landscape Ecology 8: 201–211.

Riitters, K. H., O'Neill, R. V., Hunsaker, C. T., Wickham, J. D., Yankee, D. H., Timmins, S. P., Jones, K. B. and Jackson, B. L. 1995. A vector analysis of landscape pattern and structure metrics. Landscape Ecol 10: 23–39.

Riitters, K. H., O'Neill, R. V., Wickham, J. D. and Jones, K. B. 1996. A note on contagion indices for landscape analysis. Landscape Ecol 11: 197–202.

Saunders, D., Hobbs, R. and Margules, C. 1991. Biological consequences of ecosystem fragmentation: a review. Cons Biol 5: 18–32.

Schmidt-Bleek, F. 1993. MIPS Re-Visited. Fresenius Env Bull 2: 407–412.

Straumann, N. 1986. Thermodynamik. Lecture Notes in Physics, Vol. 265, Springer-Verlag, Berlin, 140 pp.

Taylor, P. D., Fahrig, L., Henein, K. and Merriam, G. 1993. Connectivity is a vital element of landscape structure. Oikos 68: 571–573.

Turner, M. G. 1989. Landscape ecology: the effect of pattern on process. Ann Rev Ecol Syst 20: 171–197.

Turner, M. G. and Gardner, R. H. (eds). 1991. Quantitative Methods in Landscape Ecology: The Analysis and Interpretation of Landscape Heterogeneity. Springer-Verlag, New York, NY, 536 pp.

Van Dorp, D. and Opdam, P. F. M. 1987. Effects of patch size, isolation and regional abundance on forest bird communities. Landscape Ecol 1: 59–73.

Wetzel, R. G. 1975. Limnology. W. B. Saunders Comp., Philadelphia, 743 pp.