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Modification of the effective mesh size for measuring landscape fragmentation to solve the boundary problem

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Abstract

Patch-based landscape metrics can be biased by the boundaries and the extent of a reporting unit if the boundaries fragment patches. We call this the “boundary problem”. The effective mesh size m_{eff} is a convenient method to quantify landscape fragmentation, that is based on the probability that two points chosen randomly in a region will be connected, e.g., not be separated by roads, railroads, or urban development. The cutting-out (CUT) procedure, used in the original computation of m_{eff}, suffers from the boundary problem because the boundaries of the reporting units are considered to be additional barriers. Therefore, m_{eff} will be underestimated, particularly if reporting units are embedded within the broader landscape. In this paper, we present a solution to overcome this limitation by a new method called “cross-boundary connections” (CBC) procedure. It attributes the connections between two points that are located in different reporting units to both reporting units. We systematically compare the CBC procedure to the CUT procedure and show that the boundary problem is intrinsic to the CUT procedure, while the CBC procedure is independent of the size and administrative boundaries of reporting units. In addition, we elucidate the superior performance of the new procedure in the case study of South Tyrol where m_{eff} is being used for sustainability reporting on the level of municipalities. The new CBC procedure eliminates the bias due to the boundaries and the size of reporting units in measuring landscape fragmentation through m_{eff}.

240 words

Key words: cross-boundary connections procedure, cutting-out procedure, scale, spatial extent, landscape metrics, landscape indices, spatial heterogeneity, environmental indicators, environmental monitoring, South Tyrol.

1. Introduction

1.1 Landscape fragmentation and indicators

Large habitat patches are important for species to sustain viable populations (e.g., Collinge 1996, 1998; Mladenoff et al. 1999; Verboom et al. 2001). As a consequence of increasing landscape fragmentation, habitat patches are breaking apart, reducing in size, and are increasingly isolated (e.g., Forman 1995). Thus landscape fragmentation is a major cause of the rapid decline of many wildlife populations (e.g., Forman and Alexander 1998; Trombulak and Frissell 2000; Forman et al. 2003). Landscape fragmentation results from the patchwork conversion and development of sites into urban or other intensively used areas, and from the linkage of these sites via linear infrastructure, such as roads and railroads. These processes create more or less isolated habitat patches, ecosystems or other land-use types embedded in a matrix of development, that in turn affect ecological interactions (i.e., ecological flows) among habitat patches (Harris 1984; Saunders et al. 1991; Forman 1995). In particular, landscape fragmentation can reduce landscape connectivity by obstructing the movement of animals across the landscape, thereby potentially affecting metapopulation dynamics (e.g., Hanski 1999) and gene flow (Gerlach and Musolf 2000; Keller and Largiadèr 2003; Keyghobadi et al. 2005). In addition, landscape fragmentation due to transportation infrastructure enhances the dispersion of pollutants and acoustic emissions, affects local climate, water balance, scenery, recreational value of landscapes, and land use (e.g., Saunders et al. 1991; Reck and Kaule 1993; Trombulak and Frissell 2000; Spellerberg 2002; Jaeger 2002; Forman et al. 2003).

The degree of landscape fragmentation has high normative relevance as an assessment criterion for anthropogenic landscape alterations (e.g., Jaeger 2002) and is therefore considered an excellent indicator for monitoring sustainability of human land use (e.g., Heinz Center 2002; O'Malley et al. 2003; Wade et al. 2003). Many landscape indices have been applied to quantify landscape fragmentation (McGarigal and Marks 1995; Riitters et al. 1995;

Haines-Young and Chopping 1996; Hargis et al. 1998; Jaeger 2000). 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}) (see section 2.1) was unreservedly appropriate as a fragmentation measure, while the suitability of the other measures was more or less severely limited (see also Jaeger (2000) for a condensed version).

1.2 The boundary problem

The boundary of a reporting unit can have a profound influence on the value of a patch-based metric. If a boundary of a reporting unit fragments patches, artificial structures are created that do not exist in the landscape. This influence increases as the extent of a reporting unit decreases relative to the size of the patches (McGarigal et al. 2002). We call this the “boundary problem”.

The boundary problem has long been recognized (e.g., Turner et al. 1989; O’Neill et al. 1996; Saura and Martínez-Millán 2001; Turner et al. 2001; Wu 2004) but little has been done to address this issue. O’Neill et al. (1996) recommended that the extent for which a metric is computed should be two to five times larger than the largest landscape patch. However, for certain applications the extent is given, e.g., in the case of administrative units. Wu (2004) claims that comparisons between landscapes using pattern indices must be principally based on the same spatial extent. However, it may also be interesting to compare reporting units that are differing in size. To enable comparisons, recent studies used windows of a fixed size (e.g., “moving windows”) in the calculation of landscape metrics (e.g., Riitters et al. 2002, Zebisch et al. 2004). However, this approach does not solve the boundary problem, as the analysis windows fragment patches and create artificial structures.

For the sustainability report of South Tyrol, indicators were calculated on the municipality level. Municipalities were embedded within the broader landscape, as they are small relative to the scale of landscape fragmentation. Thus when considered as additional fragmentors of the landscape, the boundaries of reporting units can lead to questionable results. Therefore, the objectives of our study were threefold: (1) to define a new calculation procedure for m_{eff} that does not exhibit a boundary problem; (2) to compare the new method with the commonly applied cutting-out (CUT) procedure and systematically investigate the influence of the boundaries on the procedures; and (3) to substantiate the superior performance of the new procedure for the sustainability monitoring of South Tyrol.

2. Definition of a new calculation procedure for m_{eff}

2.1 Effective mesh size: original method

The application of m_{eff} requires the selection of pertinent fragmenting landscape elements, as well as the selection of the level at which fragmentation should be calculated, e.g., federal state level, rural districts or ecoregions (Gulinck and Wagendorp 2002).

The effective mesh size (m_{eff}) is based on the probability that two points chosen randomly in a region will be connected (i.e., be located in the same patch), which can be interpreted as the probability that two animals, placed in different locations somewhere in a region, can find each other within the region without having to cross a barrier such as a road, railroad, or urban area (Jaeger 2000). If one of the points (or both) is located within a fragmenting landscape element, for example in urban area, it is separated from the other point. By multiplying this probability by the total area of the reporting unit, it is converted into the size of an area: the effective mesh size. m_{eff} can be interpreted as the expected size of the area that is accessible when starting a movement at a randomly chosen point inside the reporting unit without encountering a physical barrier. Thus, more barriers in the landscape lower the probability that two points will be connected and lower m_{eff}. In the original computation of m_{eff}, called the cutting-out (CUT) procedure (like a cookie cutter), the boundary of the reporting unit was treated as an additional physical barrier (Jaeger et al. 2001; Peter and Meier 2003; Roedenbeck et al. 2005).

m_{eff} is mathematically defined by

$$m_{\text{eff}} = A_{\text{total}} \cdot \sum_{i=1}^{n} \left(\frac{A_i}{A_{\text{total}}} \right)^2 = \frac{1}{A_{\text{total}}} \sum_{i=1}^{n} A_i^2 \qquad (1)$$

where n = number of patches inside the reporting unit; A_i = sizes of the n patches (i = 1, …, n); A_{total} = total area of the reporting unit, e.g., of the municipality (i.e., within its boundaries). The value of m_{eff} varies between 0 (when the reporting unit is totally covered by transportation infrastructure and development, i.e., entirely fragmented) and the total area of the reporting unit (A_{total}).

In certain cases, the effective mesh size equals the area-weighted mean patch size (*AWMPS*, equation 2),

$$AWMPS = \sum_{i=1}^{n} \frac{A_i}{A} \cdot A_i \qquad (2)$$

i.e., if A in the denominator is A_{total} (and not $A_{\text{sum}} = \sum_{i=1}^{n} A_i$; these are not the same because of the area occupied by the fragmenting elements).

2.2 The new cross-boundary connections (CBC) procedure

The CBC procedure considers all patches that are wholly or partially located in the reporting unit. The latter are attributed to the reporting unit in the calculation of m_{eff} according to its share of these patches (see eq. 3). The connections across the boundary of the reporting unit indicate whether or not the patches at the boundary are fragmented and need to be included in calculating m_{eff} (Fig. 1). For example, if a landscape is un-fragmented then any two points in that landscape will be connected and the effective mesh size equals the size of that landscape (up to its physical borders). A reporting unit that is embedded in that un-fragmented landscape contains points all of which are connected to all points in that landscape (not just within the reporting unit). This is true regardless of the size of the reporting unit. Ideally, the effective mesh size of the reporting unit should be equal to the size of the landscape. Therefore, m_{eff} calculated according to the CBC procedure includes connections between one point chosen randomly in the reporting unit with another randomly chosen point which can be within the area covered by the *complete* patches, i.e., including those parts of the patches that are outside of the reporting unit. Hence, m_{eff} can be interpreted as the expected size of the area that is accessible when starting a movement at a randomly chosen point inside the reporting unit without encountering a physical barrier. Therefore in the CBC procedure, all connections between any two points are taken into account by some reporting unit (Fig. 1) with no connections neglected, unlike in the CUT procedure.

In contrast to the CUT procedure, the boundary of the reporting unit is not considered a barrier because connections that cross the reporting unit's boundary are included. The question thus is how many other points a randomly chosen point in the reporting unit is connected to. As a consequence, the value of the effective mesh size can be larger than the reporting unit, but not larger than the largest patch that is touched by the reporting unit. Another rationale for this approach is that in a landscape where all patches are of the same size (e.g., a regular grid), m_{eff} in the original definition always equals the size of the patches if the boundary of the reporting unit follows the edges of some patches. The modified definition generalizes this observation to be true also in cases when the reporting units are shifted or rotated, or when the reporting units are smaller than the patches.

The formula of m_{eff} according to the CBC procedure is:

$$m_{\text{eff}}^{\text{CBC}} = A_{\text{total}}^{\text{cmpl}} \cdot \sum_{i=1}^{n} \left(\frac{A_i}{A_{\text{total}}} \cdot \frac{A_i^{\text{cmpl}}}{A_{\text{total}}^{\text{cmpl}}} \right) = \frac{1}{A_{\text{total}}} \sum_{i=1}^{n} A_i \cdot A_i^{\text{cmpl}} \qquad (3)$$

where n = the number of patches, A_i = size of patch i inside the boundaries of the reporting unit (i = 1, 2, 3, …, n), A_i^{cmpl} = the area of the complete patch that A_i is a part of, i.e., including the area on the other side of the boundaries of the reporting unit up to the physical barriers of the patch (Fig. 1; if A_i is entirely located within the reporting unit and not bordered by the reporting unit's boundary then $A_i^{\text{cmpl}} = A_i$), A_{total} = the total area of the reporting unit, and $A_{\text{total}}^{\text{cmpl}}$ = the total area covered by the complete patches. The term A_i / A_{total} equals the probability that the first point chosen randomly within the reporting unit will be located in patch i (with area A_i). The term $A_i^{\text{cmpl}} / A_{\text{total}}^{\text{cmpl}}$ equals the probability that the second point chosen randomly in the area covered by the complete patches will be located in the complete patch i (with area A_i^{cmpl}). Multiplication of the connection probability by $A_{\text{total}}^{\text{cmpl}}$ is appropriate to convert it to an area that can be interpreted as outlined above. The consideration of boundary patches according to the reporting unit's share of area, is expressed by the term

$$A_i^{\text{cmpl}} \cdot \frac{A_i}{A_{\text{total}}} \quad . \qquad (4)$$

Figure 1 (approximately here)

Figure 1 shows an example where $m_{\text{eff}}^{\text{CBC}}$ for reporting unit 1 is calculated by

$$\begin{aligned} m_{\text{eff}}^{\text{CBC}} &= \frac{1}{A_{\text{total}}}\left(A_1 \cdot A_1^{\text{cmpl}} + A_2 \cdot A_2^{\text{cmpl}} + A_3 \cdot A_3^{\text{cmpl}} + \ldots + A_n \cdot A_n^{\text{cmpl}}\right) \\ &= \frac{1}{70\ \text{km}^2}\left(18 \cdot 18\ \text{km}^4 + 30 \cdot 30\ \text{km}^4 + 20 \cdot 50\ \text{km}^4\right) = \frac{2224\ \text{km}^4}{70\ \text{km}^2} = 31.77\ \text{km}^2. \end{aligned}$$

This value is larger than the value from the CUT procedure (which would be 23.2 km^2).

$m_{\text{eff}}^{\text{CBC}}$ is intensive and strictly area-proportionately additive . These simple mathematical properties (cf. Chandler 1987, pp. 22-25; Legendre and Legendre 1998, p. 31) transferred to landscape pattern indices have interesting consequences for the use of the measures. Being ‘intensive’ means remaining constant when the analysed region is being multiplied but keeping its structure (i.e., multiplying the number of patches accordingly). ‘Area-proportionately additive’ means that each reporting unit contributes to the combination of two or more reporting units proportionally to its size, even if each reporting unit has a different spatial structure. These properties also hold true if large patches are located across the boundaries of the reporting units (proof in Appendix A). Accordingly, $m_{\text{eff}}^{\text{CBC}}$ can be calculated for the combination of two or more reporting units from the individual effective mesh sizes of these regions, by calculating the area-weighted mean value.

3. The boundary problem: comparing the CBC and the CUT procedure

If a reporting unit is subdivided into two parts by an administrative boundary, the degree of landscape fragmentation of the entire area should be between the values of its two parts (let part 1 denote the part that has the lower degree of landscape fragmentation than the other part):

$$DF_{\text{part 1}} \leq DF_{\text{total}} \leq DF_{\text{part 2}}, \tag{5}$$

where $DF_{\text{part 1}}$ = degree of landscape fragmentation measured for part 1; $DF_{\text{part 2}}$ = degree of landscape fragmentation measured for part 2; DF_{total} = degree of landscape fragmentation measured for the entire reporting unit.

Figure 2 (approximately here)

We systematically investigated the behavior of the CUT and CBC procedures with respect to the above mentioned condition. We analyzed two simple landscapes (Fig. 2) to demonstrate that the CUT procedure does not meet the condition defined in eq. (5). We also performed a mathematical proof to demonstrate that the CBC procedure always meets the condition in eq. (5). According to the CUT procedure, the boundary artificially fragmented the patches in the center (Fig. 2). Therefore, the m_{eff} values for the two parts were lower than the value for the entire reporting unit. Hence, the CUT procedure will meet the condition described above only if the boundary does not dissect a patch, e.g., if the boundary coincides with the edges of landscape patches. However, this is usually not the case.

According to the CBC procedure, a boundary does not fragment the connections within patches. A boundary patch contributes to each part according to its share within the part. According to the new procedure $m_{\text{eff, combined}}$ can be calculated from the area-weighted mean of the two parts, as the CBC procedure is an area-proportionately additive quantity (see section

2.2 and Appendix A). Given that the two parts are equal in size, as in our pattern series (Fig. 2), $m_{\text{eff, combined}}$ results in $m_{\text{eff, combined}} = (m_{\text{eff, part 1}} + m_{\text{eff, part 2}})/2$.

For pattern series a), $m_{\text{eff ,part 1}} = m_{\text{eff ,part 2}} = m_{\text{eff, combined}}$ as $m_{\text{eff}}^{\text{CBC}}$ remains constant when the extent is changed but the structure is kept constant.

The general proof that $m_{\text{eff}}^{\text{CBC}}$ meets condition (eq. 5) is based on the property that $m_{\text{eff}}^{\text{CBC}}$ is area-proportionately additive. Let $m_{\text{eff, part 1}}$ and $m_{\text{eff, part 2}}$ be effective mesh sizes of the two parts (and let $m_{\text{eff, part 1}}$ be the lower value). Because the effective mesh size of the combined reporting unit is given by

$$m_{\text{eff, combined}}^{\text{CBC}} = \frac{A_{\text{total}}^{\text{part 1}}}{A_{\text{total}}^{\text{part 1}} + A_{\text{total}}^{\text{part 2}}}\, m_{\text{eff, part 1}} + \frac{A_{\text{total}}^{\text{part 2}}}{A_{\text{total}}^{\text{part 1}} + A_{\text{total}}^{\text{part 2}}}\, m_{\text{eff, part 2}},$$

it directly follows that $m_{\text{eff, part 1}} \le m_{\text{eff, combined}}^{CBC} \le m_{\text{eff, part 2}}$. This proves that the CBC procedure always meets the required condition.

4. Case study South Tyrol

To compare and evaluate the performance of the CBC and CUT procedures under real conditions, we applied m_{eff} according to both procedures in the framework of the regional sustainability monitoring of South Tyrol.

4.1 Study site and calculations

South Tyrol covers an area of 7,400 km² with a typical alpine geo-morphology (Fig. 3 a). Sixty percent of the terrain is higher than 1600 meters above sea level. Only 8.3 % of the area can be used for permanent settlement, partly due to its steep mountainous character. The road and railroad network accounts for a direct loss of 0.53 % of the total area's habitat, while urban development amounts to only 0.15 %. For the sustainability monitoring of South Tyrol, the units of investigation were defined by the 116 municipalities of the region, varying in size from 1.6 km² to 302.3 km².

Figure 3 (approximately here)

In the calculations, we included the road and railway network (Autonomous Province of South Tyrol 2001), the areas of development (Autonomous Province of South Tyrol 1991a) (Fig. 3 b and c), and the municipality boundaries (Autonomous Province of South Tyrol 1991b). We generated a binary categorical map for calculating m_{eff} according to the CBC and CUT procedures. Areas of urban development and transportation infrastructure were considered fragmenting elements. Roads (ranging from municipal roads to motorways) and railway lines were included according to their width (e.g., 6 meters for municipal roads, to 24 meters for motorways). As data were only available for within South Tyrol, patches adjacent to the region's boundaries were cropped, causing them to appear smaller than they actually are. The calculations of m_{eff} were conducted in ArcView using an existing tool of AVENUE scripts (Esswein et al. 2002, 2003). We adapted the tool for the calculation of the CBC procedure (scripts available from the authors).

4.2 Comparison of $m_{\text{eff}}^{\text{CBC}}$ and $m_{\text{eff}}^{\text{CUT}}$ for South Tyrol

The value of the effective mesh size in South Tyrol is 495 km^2. For most municipalities, the values of m_{eff} calculated according to the CBC procedure differed greatly from those calculated according to the CUT procedure.

Figure 4 (approximately here)

Values for the CUT procedure ranged from 0.5 km² to 208.7 km². Values for the CBC procedure ranged from 2.1 km² to 1,065 km² (Fig. 4). $m_{\text{eff}}^{\text{CUT}}$ showed a clear correlation with municipality size ($R^2 = 0.7987$), $m_{\text{eff}}^{\text{CBC}}$ was almost independent ($R^2 = 0.172$) (Fig. 4). However, a slight trend of increasing $m_{\text{eff}}^{\text{CBC}}$ with increasing municipality size remained (not significant). This trend was not an effect of the calculation method but a consequence of a characteristic of the study area; municipality size is usually small in the valleys exhibiting a dense network of development and transport facilities, while municipality size is usually large in mountainous areas with sparse development.

When comparing m_{eff} computed for the entire region of South Tyrol ($m_{\text{eff total}}$) to the area-weighted mean of all m_{eff} values calculated individually for the municipalities ($AWM\_m_{\text{eff mun}}$), calculated according to the CUT procedure, $AWM\_m_{\text{eff mun}}$ was considerably lower than $m_{\text{eff total}}$ ($AWM\_m_{\text{eff mun}}^{\text{CUT}}$ = 73 km², $m_{\text{eff total}}$ = 495 km²). On the contrary, the CBC procedure delivered equal values according to both methods ($AWM\_m_{\text{eff mun}}^{\text{CBC}} = m_{\text{eff total}}$ = 495 km²).

Figure 5 (approximately here)

The spatial distribution exhibited a comparatively high heterogeneity for $m_{\text{eff}}^{\text{CUT}}$ (Fig. 5 a). The sparsely populated mountainous areas in the Northeast and the West obtain high values. But high values were also found in some large municipalities in the central valleys. In contrast to $m_{\text{eff}}^{\text{CUT}}$, the results for the CBC procedure revealed a spatial clustering (Fig. 5 b). Three groups were distinguished: (a) municipalities with high $m_{\text{eff}}^{\text{CBC}}$ in the sparsely populated mountainous areas in the Northeast and the West; (b) moderate $m_{\text{eff}}^{\text{CBC}}$ in the central valleys with moderate population densities but major transportation axes, (c) low $m_{\text{eff}}^{\text{CBC}}$ in the densely populated lowland areas in the South. Compared to the CUT procedure, fewer municipalities fell into the two lower classes.

5. Discussion

We defined a new calculation procedure for m_{eff} called the CBC procedure. Our analytical comparison showed that the boundary problem is intrinsic to the CUT procedure, while the CBC procedure is independent of the size and administrative boundaries of reporting units. For the CBC procedure, the characteristic of being area-proportionately additive not only proves this independence of spatial extent, but also makes $m_{\text{eff}}^{\text{CBC}}$ particularly helpful in comparing the fragmentation of regions of different sizes, assessing the influence of parts of a region compared to the fragmentation of the total region, and aggregating fragmentation values of several regions of differing sizes (see section 2.2).

Applying the new procedure, large landscape patches are appropriately considered, even if they are larger than reporting units. This is a great improvement over the CUT procedure, due to the importance of large patches for species to sustain viable populations (e.g. Collinge 1996, 1998; Mladenoff et al. 1999; Verboom et al. 2001). Some landscape ecologists might question the consideration of landscape patches that are partially located outside the reporting unit. However, we argue that metrics, to the highest possible degree, should be calculated based on the patch pattern that is relevant for the ecological process under consideration (Haines-Young and Chopping 1996; Li and Wu 2004). Therefore, patches should not be cropped deliberately, but should be considered according to their properties, whether they are covered by the reporting unit wholly or partially. Considering boundary patches beyond the boundaries may lead to changes of a metric's value by actions taken outside the reporting unit. This is appropriate as reporting units do not exist in isolation but are embedded in a broader landscape context which has ecological relevance.

Li and Wu (2004) claimed that "interpreting indices remains difficult because the merits and caveats of landscape metrics remain poorly understood". Moreover, the authors state that the "most critical limitation for the use of landscape metrics is the ecological irrelevance of landscape indices or map data and the variable responses of indices to changing landscape patterns". We argue that the CBC procedure for applying m_{eff} is a method for quantifying landscape fragmentation that is well understood, ecologically relevant, and suitable for its designated task.

The case study of South Tyrol demonstrated the superior performance of $m_{\mathrm{eff}}^{\mathrm{CBC}}$ in an empirical application. In contrast to $m_{\mathrm{eff}}^{\mathrm{CUT}}$, $m_{\mathrm{eff}}^{\mathrm{CBC}}$ is not limited by municipality size. Values of municipalities can be aggregated without causing bias.

Environmental policies have been released that have the aim of avoiding further fragmentation of intact zones (e.g., UN Convention on Biological Diversity, Pan-European Biological and Landscape Diversity Strategy). In this respect, m_{eff} results calculated according to the CUT procedure may lead to different conclusions than those based on the CBC procedure. According to the CUT procedure, the attention for protection would be drawn to large municipalities which happen to cut out the largest parts of patches. In contrast, the CBC procedure indicates large non-fragmented zones for protection independently of municipality size. The new CBC procedure combines two important criteria for using the indicator of landscape fragmentation: First, reference to political boundaries is important for communication of results to decision-makers because they can compare the results of their municipality with other municipalities. Thus, communication between municipalities may be encouraged. Second, municipality boundaries do not erroneously influence fragmentation values. Hence, procedures such as the $m_{\text{eff}}^{\text{CBC}}$ are essential for application where reporting units are embedded within a broader landscape.

The CBC procedure presented in this paper is geared specifically to m_{eff}. However, the principle of the procedure, that is, to overcome the boundary problem by including connections crossing the reporting unit's boundary, may be applied to other patch based metrics.

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Appendix A. Some useful characteristics of the CBC procedure

A.1 Definitions

A landscape metric, say *F*, is called '***intensive***', if $F(\lambda \cdot \Phi) = F(\Phi)$ 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 (cf. Chandler 1987, pp. 22-25; Legendre and Legendre 1998, p. 31). For example, 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.

A landscape metric, say *F*, is called '***area-proportionately additive***' if the value of *F* for the combination of two area configurations Φ_1 and Φ_2 (with total areas $A^{(1)}_{\text{total}}$ and $A^{(2)}_{\text{total}}$) is given by

$$F(\Phi_1 \cup \Phi_2) = \frac{A^{(1)}_{\text{total}}}{A^{(1)}_{\text{total}} + A^{(2)}_{\text{total}}} \cdot F(\Phi_1) + \frac{A^{(2)}_{\text{total}}}{A^{(1)}_{\text{total}} + A^{(2)}_{\text{total}}} \cdot F(\Phi_2).$$

This is analogous to the way the 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. This means that each part (e.g., Φ_1 and Φ_2) contributes proportionally to its size, even if each part has a different spatial structure.

The characteristics of being intensive or area-proportionately additive are interrelated. 'Area-proportionately additive' means more than 'intensive'. In fact, every area-proportionately additive quantity is intensive. The reverse generally does not hold. Average patch size is an example of an intensive measure which is not area-proportionately additive.

A.2 On the case that two or more parts of a patch are located within a reporting unit

Whether the parts of a patch that are located within a reporting unit are connected inside or only outside the reporting unit does not influence the value of m_{eff}.

Proof: Let A_1 and A_2 be two parts of a single patch that are located within a reporting unit, as shown in Fig. 6.

Figure 6 (approximately here)

The general formula of m_{eff} according to the CBC procedure (see eq. 3 from page 8) is $m_{\text{eff}}^{\text{CBC}} = \frac{1}{A_{\text{total}}} \sum_{i=1}^{n} A_i \cdot A_i^{\text{cmpl}}$. In the case shown in Fig. 6, it holds $A_1^{\text{cmpl}} = A_2^{\text{cmpl}}$, and thus,

$$
\begin{aligned}
m_{\text{eff}}^{\text{CBC}} &= \frac{1}{A_{\text{total}}} \left(A_1 \cdot A_1^{\text{cmpl}} + A_2 \cdot A_1^{\text{cmpl}} + A_3 \cdot A_3^{\text{cmpl}} + \ldots + A_n \cdot A_n^{\text{cmpl}} \right) \\
&= \frac{1}{A_{\text{total}}} \left(\left(A_1 + A_2 \right) \cdot A_1^{\text{cmpl}} + A_3 \cdot A_3^{\text{cmpl}} + \ldots + A_n \cdot A_n^{\text{cmpl}} \right).
\end{aligned}
$$

Consequently, the value of m_{eff} according to the cross-boundary connection procedure is the same in both cases if A_1 and A_2 are disconnected within the reporting unit, or if they are connected, i.e., one patch size of ($A_1 + A_2$). The same is true if the number of parts within the reporting unit is larger than two. The value of m_{eff} does not depend on the number of fractions that are cut away by boundaries of a reporting unit, because the probability that a randomly chosen point is found within a group of several fractions of a patch within a reporting unit equals the sum of these fractions. The connections between two points, located one in A_1 and the other in A_2, are not affected by whether they are running within or outside of the reporting unit.

A.3 On the mathematical property of $m_{\text{eff}}^{\text{CBC}}$ to be area-proportionately additive

The effective mesh size, when calculated according to the CBC procedure, is an area-proportionately additive quantity without any restrictions.

Proof: Let Φ_1 and Φ_2 be two area distributions $\Phi_1 = \left\{ A_i^{(1)} \middle| \, i = 1,\ldots,n_1 \right\}$, $\Phi_2 = \left\{ A_i^{(2)} \middle| \, i = 1,\ldots,n_2 \right\}$ with total areas $A_{\text{total}}^{(1)}$ and $A_{\text{total}}^{(2)}$. The joint configuration $\Phi_1 \cup \Phi_2$ has n_3 patches where $n_3 \le n_1 + n_2$ because either none of the patches has parts located in Φ_1 and Φ_2 at the same time (and then $n_3 = n_1 + n_2$), or one or more of the patches have parts located in Φ_1 and Φ_2 at the same time (and then $n_3 < n_1 + n_2$). In the first case, all $A_i^{(1),\text{cmpl}}$ are different from all $A_j^{(2),\text{cmpl}}$, and m_{eff} of the joint configuration $\Phi_1 \cup \Phi_2$ results in

$$
\begin{aligned}
m_{\text{eff}}\left(\Phi_1 \cup \Phi_2\right) &= \frac{1}{A_{\text{total}}^{(1)} + A_{\text{total}}^{(2)}} \left(\sum_{i=1}^{n_1} \left(A_i^{(1)} \cdot A_i^{(1),\text{cmpl}} \right) + \sum_{j=1}^{n_2} \left(A_j^{(2)} \cdot A_j^{(2),\text{cmpl}} \right) \right) \\
&= \frac{A_{\text{total}}^{(1)}}{A_{\text{total}}^{(1)} + A_{\text{total}}^{(2)}} \frac{1}{A_{\text{total}}^{(1)}} \sum_{i=1}^{n_1} \left(A_i^{(1)} \cdot A_i^{(1),\text{cmpl}} \right) + \frac{A_{\text{total}}^{(2)}}{A_{\text{total}}^{(1)} + A_{\text{total}}^{(2)}} \frac{1}{A_{\text{total}}^{(2)}} \sum_{j=1}^{n_2} \left(A_j^{(2)} \cdot A_j^{(2),\text{cmpl}} \right) \\
&= \frac{A_{\text{total}}^{(1)}}{A_{\text{total}}^{(1)} + A_{\text{total}}^{(2)}} \cdot m_{\text{eff}}\left(\Phi_1\right) + \frac{A_{\text{total}}^{(2)}}{A_{\text{total}}^{(1)} + A_{\text{total}}^{(2)}} \cdot m_{\text{eff}}\left(\Phi_2\right).
\end{aligned}
$$

In the second case, there are patches with $A_i^{(1),\text{cmpl}} = A_j^{(2),\text{cmpl}}$, and either $A_i^{(1)}$ and $A_j^{(2)}$ are connected or not connected (as shown in Fig. 6). In either case, their contribution to m_{eff} is the same as $A_i^{(1)} \cdot A_i^{(1),\text{cmpl}} + A_j^{(2)} \cdot A_j^{(2),\text{cmpl}} = \left(A_i^{(1)} + A_j^{(2)}\right) \cdot A_i^{(1),\text{cmpl}} = A_k^{(1+2)} \cdot A_k^{(1+2),\text{cmpl}}$ as discussed above (in section A.2). Therefore, the sum $\sum_{k=1}^{n_3} \left(A_k^{(1+2)} \cdot A_k^{(1+2),\text{compl}} \right)$ can be written as the two sums $\sum_{i=1}^{n_1} \left(A_i^{(1)} \cdot A_i^{(1),\text{cmpl}} \right) + \sum_{j=1}^{n_2} \left(A_j^{(2)} \cdot A_j^{(2),\text{cmpl}} \right)$, and the relationship above is also valid, i.e., $m_{\text{eff}}\left(\Phi_1 \cup \Phi_2\right) = \frac{A_{\text{total}}^{(1)}}{A_{\text{total}}^{(1)} + A_{\text{total}}^{(2)}} \cdot m_{\text{eff}}\left(\Phi_1\right) + \frac{A_{\text{total}}^{(2)}}{A_{\text{total}}^{(1)} + A_{\text{total}}^{(2)}} \cdot m_{\text{eff}}\left(\Phi_2\right)$. This means that $m_{\text{eff}}^{\text{CBC}}$ is an area-proportionately additive quantity.

Figure Captions

Figure 1. Example of calculating m_{eff} according to the CBC procedure for reporting unit 1 (R_1). (a) Connections between locations within A_3 (inside R_1) are included in m_{eff} . (b) Connections between locations outside of R_1 are not included in m_{eff} . (c) Connections crossing the boundary and starting in R_1 are included in m_{eff}. (d) Connections crossing the boundary and starting in R_2 are not included in m_{eff}. A_1 does not include the urban area; A_{total} of R_1 includes A_1, A_2, A_3, and the urban area; A_i^{cmpl} includes A_i.

(A_1 = 4 km * 5 km – 2 km * 1 km = 18 km², A_1^{cmpl} = 18 km², A_2 = 6 km * 5 km = 30 km², A_2^{cmpl} = 30 km², A_3 = 10 km * 2 km = 20 km², A_3^{cmpl} = 10 km * 5 km = 50 km², $A_{\mathrm{total}}(R_1)$ = 10 km * 7 km = 70 km²)

$m_{\mathrm{eff}}^{\mathrm{CBC}}$ of R_1 is calculated as 31.77 km^2 (see text).

The connections described above within landscape patch A_3^{cmpl} are assigned to reporting units R_1 and R_2 differently according to the CUT procedure or the CBC procedure. The CUT procedure does not assign two types of connections to any reporting unit. In contrast, the CBC procedure assigns all types of connections to some reporting unit.

Figure 2. Effect of subdividing the reporting unit on the value of m_{eff} according to the CUT and CBC procedures. An additional boundary runs through a landscape with a distinct fragmentation pattern (left), dividing the total area (A_{total}) in two halves. In example a), the landscape structure is a regular grid. According to the CUT procedure, $m_{\mathrm{eff,\ part}}$ is lower than $m_{\mathrm{eff,\ combined}}$. According to the CBC procedure, $m_{\mathrm{eff,part}}$ equals $m_{\mathrm{eff,combined}}$. In example b), the fragmentation pattern is not regular. $m_{\mathrm{eff,\ part}}^{\mathrm{CUT}}$ is again lower than $m_{\mathrm{eff,\ combined}}^{\mathrm{CUT}}$ in both parts. When

applying the CBC procedure, m_{eff} is higher in part 1 than for the total landscape and part 2 receives a lower value.

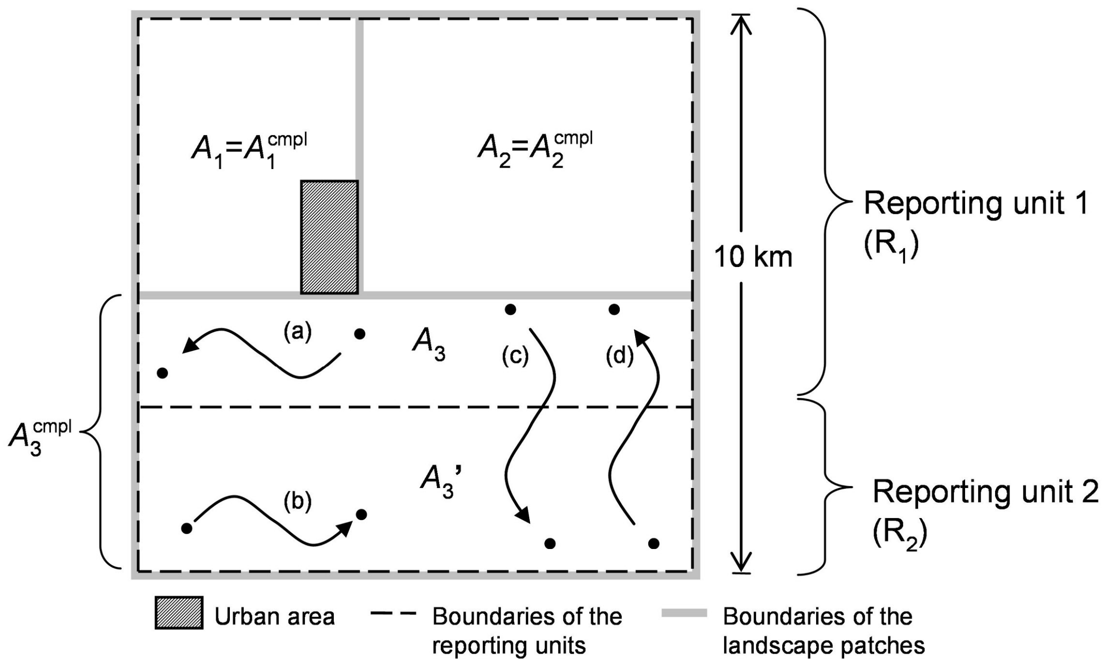
Figure 3. Study area of South Tyrol. a) Location of the study area. b) Elements fragmenting the landscape (road and railway network, areas of development). c) Municipality boundaries.

Figure 4. Effective mesh size according to CUT procedure and CBC procedure plotted against municipality size for the 116 municipalities of South Tyrol. R^2 is Pearson's correlation value. For the CUT procedure, many values are near the dotted line indicating the maximum possible value for $m_{\mathrm{eff}}^{\mathrm{CUT}}$ (= municipality size).

Figure 5. Geographic distribution of m_{eff} values in the 116 municipalities in South Tyrol according to (a) the CUT procedure and (b) the CBC procedure. For both procedures, the values are indicated by 11 equally sized classes, each class covering 20 km² for (a) and 100 km² for (b).

Figure 6. Two or more parts of a patch located within a reporting unit. Whether these parts are connected or subdivided into several fractions does not influence the value of $m_{\mathrm{eff}}^{\mathrm{CBC}}$.

Figure 1.



Procedure	Connections within A_3^{cmpl}			
	a) inside R_1	b) inside R_2	c) from R_1 to R_2	d) from R_2 to R_1
CUT procedure	assigned to R_1	assigned to R_2	neglected	neglected
CBC procedure	assigned to R_1	assigned to R_2	assigned to R_1	assigned to R_2

588

592

596 Figure 2.

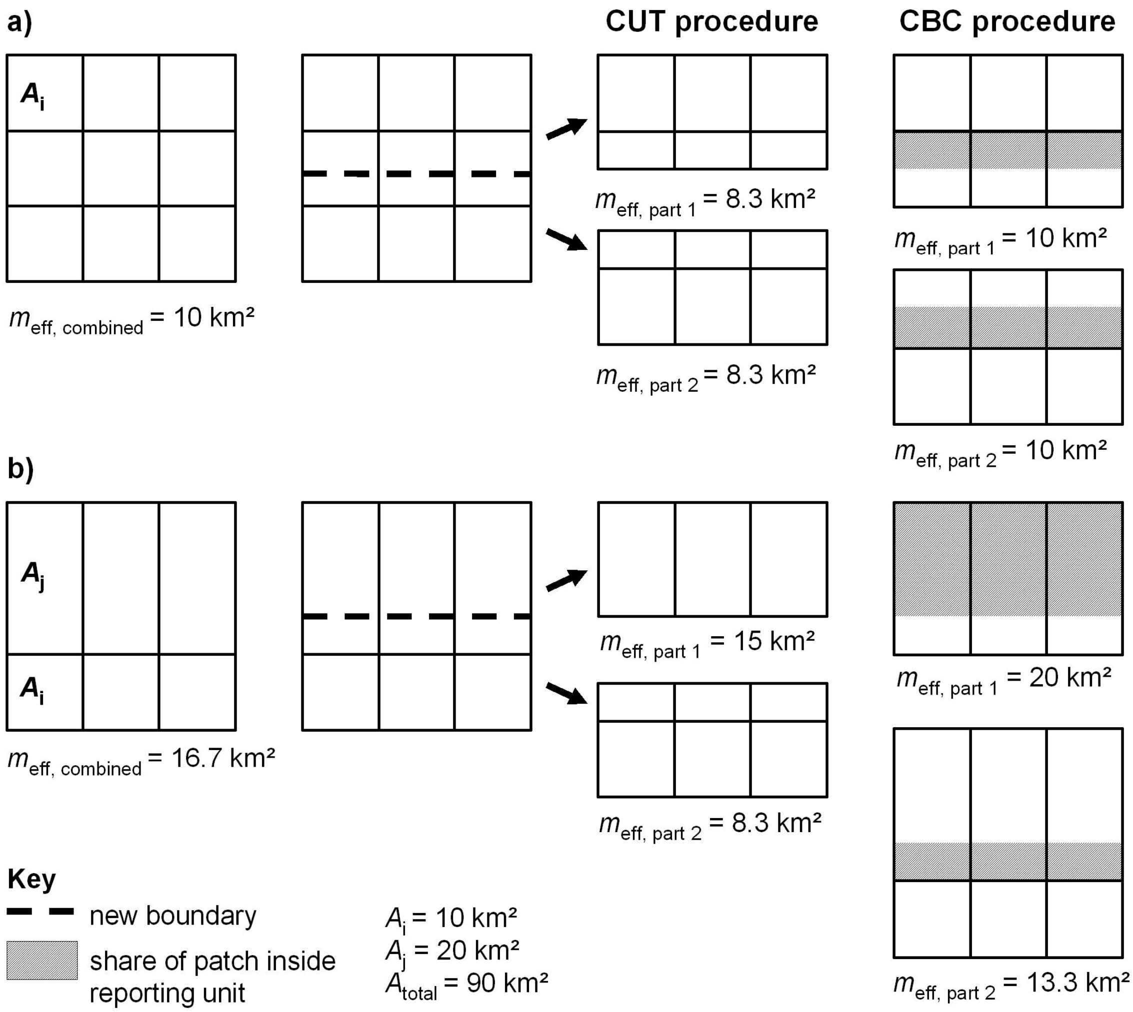
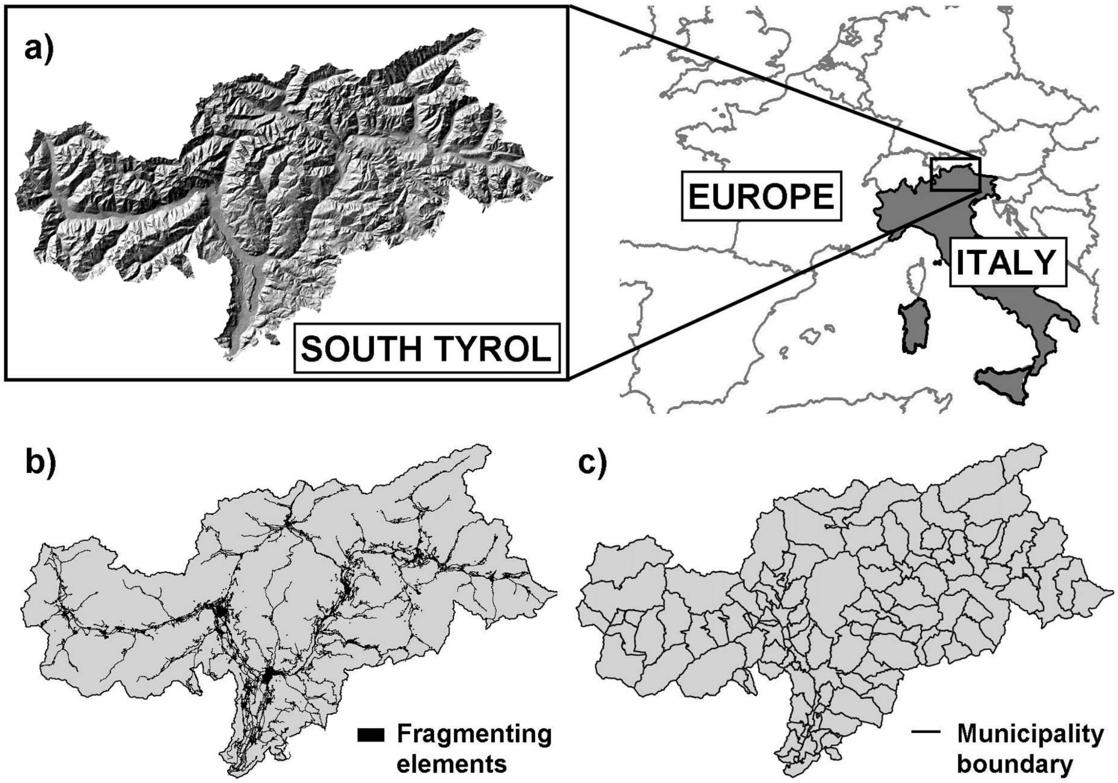
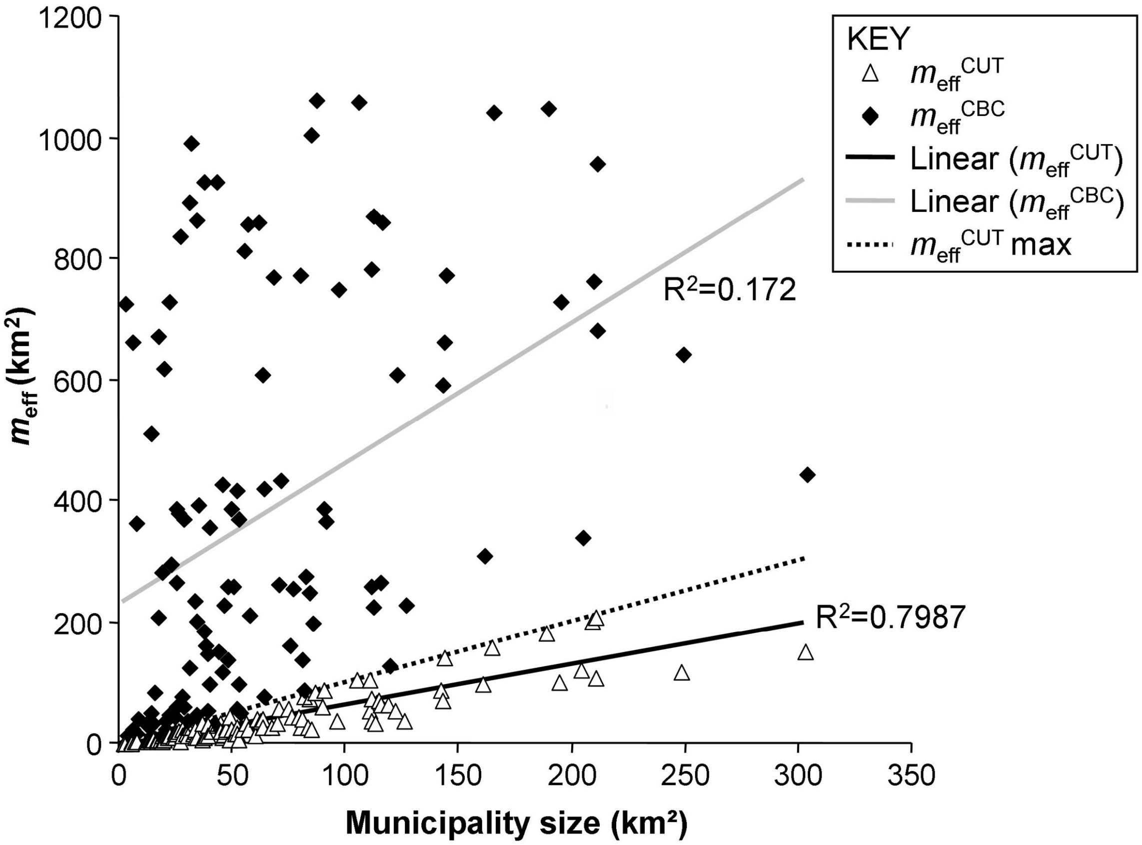

a)
CUT procedure
CBC procedure
A_i
m_eff, combined = 10 km²
m_eff, part 1 = 8.3 km²
m_eff, part 2 = 8.3 km²
m_eff, part 1 = 10 km²
m_eff, part 2 = 10 km²
b)
A_j
A_i
m_eff, combined = 16.7 km²
m_eff, part 1 = 15 km²
m_eff, part 2 = 8.3 km²
m_eff, part 1 = 20 km²
m_eff, part 2 = 13.3 km²
Key
new boundary
share of patch inside reporting unit
A_i = 10 km²
A_j = 20 km²
A_total = 90 km²

Figure 3.


a)
SOUTH TYROL
EUROPE
ITALY
b)
Fragmenting elements
c)
Municipality boundary

600

Figure 4.


1200
1000
800
600
400
200
0
m_{eff} (km²)
0
50
100
150
200
250
300
350
Municipality size (km²)
KEY
m_{eff}^{CUT}
m_{eff}^{CBC}
Linear (m_{eff}^{CUT})
Linear (m_{eff}^{CBC})
m_{eff}^{CUT} max
R^2=0.172
R^2=0.7987

604

Figure 5.

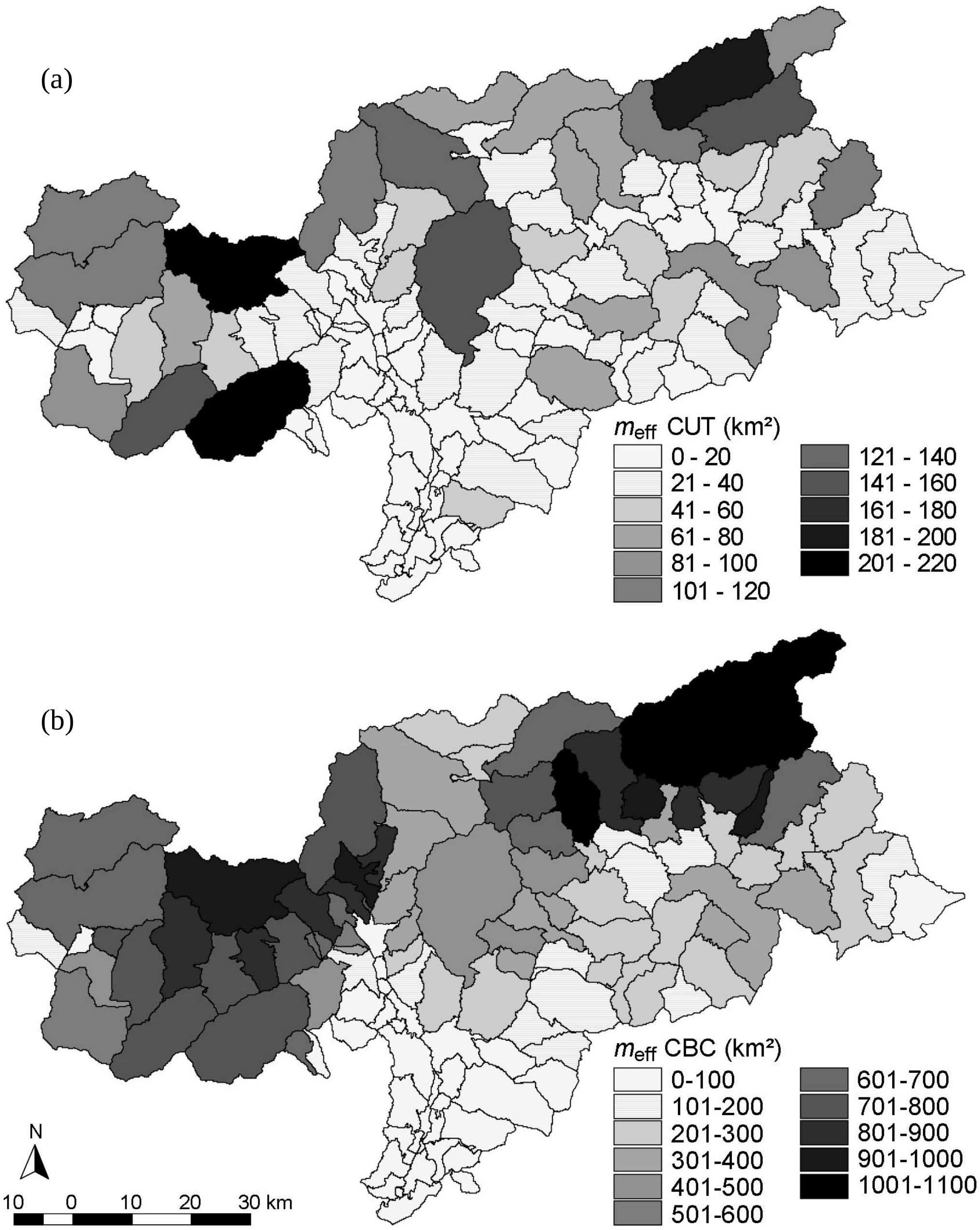
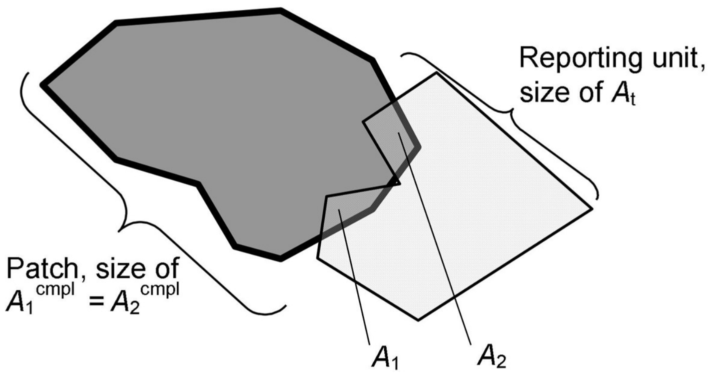

(a)
m_{eff} CUT (km²)
0 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121 - 140
141 - 160
161 - 180
181 - 200
201 - 220
(b)
m_{eff} CBC (km²)
0-100
101-200
201-300
301-400
401-500
501-600
601-700
701-800
801-900
901-1000
1001-1100
N
10 0 10 20 30 km

Figure 6.



612