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Holistic aspects of suburban landscapes: visual image interpretation and landscape metrics

Marc Antrop*, Veerle Van Eetvelde

Department of Geography, University Ghent, Krijgslaan 281 S8, B9000 Gent, Belgium

Abstract

Holism deals with extremely complex structures that are difficult to analyse. The holistic approach of landscape research was stimulated by the introduction of aerial photography. Carl Troll called ''aerial photo-interpretation as a high degree of landscape ecology,'' which illustrates the intimate link between the bio-philosophical theory of holism and the Gestalt-theory of human perception, which is important in image interpretation. Aerial photography proved to be a valuable instrument, not only to make thematic inventories and monitor changes, but also to describe holistic aspects of complex landscapes. Contrarily, the analytical approach aims to describe transcendent characteristics of complex structures by quantitative variables. Many landscape metrics have been proposed and used, such as entropy as an indicator of fragmentation and heterogeneity.

A comparison was made between a typology and classification of a highly complex suburban landscape with aid of a holistic-based approach for visual interpretation of aerial photographs and a quantitative approach using landscape metrics of the patches formed by the land use. The study area covers the suburban transition of the city of Ghent (Flanders, Belgium) to the rural countryside to the west and is characterised by a large diversity of land use and a severe fragmentation of infrastructures. The visual interpretation of aerial photographs allowed rapid and easy classification into 10 distinct and landscape types, which could be mapped. The landscape metrics used were patch area, patch shape, fractal dimension of the patch borders and two forms of information entropy. The metrics were derived from the land use map based upon a supervised classification of satellite data and improved by ancillary data with a resolution of 20 m. Overall, the fractal dimension and entropy are significantly different for the landscape types, while those for the patch area and shape are not. Landscape metrics are very sensitive to data quality, particularly in complex and very heterogeneous landscapes. Interpretation of the results is also made more difficult due to the effects caused by the algorithms of spatial analysis used to determine patches, and due to the noise added by index calculation. These effects are reflected on maps representing the distribution of the landscape metrics. The patterns revealed here depend largely upon the method of classification and visualisation. The summed entropy corresponds most closely to the landscape units defined by visual image interpretation. It can be used as a quantitative characteristic of holistically defined landscape units. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Holism; Landscape ecology; Landscape metrics; Suburban landscape

1. Introduction

Holism is considered to be a fundamental characteristic of landscape ecology (Naveh and Lieberman, 1994; Antrop, 1996). Its theory states that the landscape should be considered a complex whole that is

* Corresponding author. Tel.: +32-9-264-47-05; fax: +32-9-264-49-85.
E-mail address: marc.antrop@rug.ac.be (M. Antrop)

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more than the sum of its composing parts. This indicates that all elements in the spatial structure of the landscape are related to each other and form one complex system. Attempts are made to quantify the purely holistic, i.e. transcendent characteristics of landscapes. These characteristics are expressed as abstract landscape metrics or indices, such as Shannon entropy or diversity, fractal dimension, and heterogeneity. Many indices have been proposed and their names and definitions vary greatly (Turner and Gardner, 1990; Hunsaker et al., 1994; Farina, 1998; Dramstad et al., 1998).

Can holistic characteristics of suburban landscapes be expressed by landscape metrics? What are the possibilities and drawbacks? Do landscape metrics mean something really holistic and are they useful? These questions were tested in the urban fringe landscape north-west of Ghent in Flanders, Belgium. First, some key concepts related to holism and urbanisation are defined. Next, the properties and quality of the available digital maps were analysed. In particular, the inventories of the built-up land, an important land use category in the suburban landscape, was studied. Our aim was to examine the difficulties of using the existing general inventories of land cover, which are often the only available data sources. Finally, some of the most common landscape metrics were calculated for the suburban landscape to determine the map patterns from spatial analysis. The key questions here were (1) do these maps reveal new characteristics of these landscapes that can be interpreted as holistic, and (2) can we use the holistic capability of visual interpretation to interpret these maps more easily?

2. Holism and image interpretation

Holism is a bio-philosophical theory that originated with the naturalists during the early 19th century. Alexander von Humboldt (1769–1859), one of the 'grandfathers' of geography and landscape ecology defined landscape as "Landschaft ist das Totalcharacter einer Erdgegend". Carl Troll called his approach an 'Anschauungsweis', a way of looking at the subject (Zonneveld, 1995). Holism was also important for Gestalt-psychology and in particular as a theory to explain how our perception works. The perceptive dimension in landscape is fundamental, as the concept of landscape combines a piece of land with its appearance, the scenery. Interaction between perception of the environment and behaviour leads to landscaping, i.e. shaping and organising land according to the needs of a (local) society and according to ethical and aesthetic values. As needs and values change, views of landscaping change accordingly. Landscape is dynamic and in continuous transition, not only by natural processes, but also by changing economical needs and cultural values.

Holism is an abstract concept and therefore difficult to handle and apply. A useful additional concept that allows its easier practical application is the concept of a holon, introduced by Naveh and Lieberman (1994), and which is closely related to the ecodevice concept (Van Wirdum, 1981). Holons are the building blocks of the Total Human Ecosystem (Naveh and Lieberman, 1994) and holism also includes a hierarchical scale context in landscape study. Hierarchical structuring of landscapes is a classic method in land evaluation and landscape classification (Zonneveld, 1995; Antrop, 1997). To reduce the extreme complexity of landscapes, a structure is composed of more comprehensive land units at different scales. An important initial task in all landscape studies is the definition of the scale at which the study will be done. This task is usually achieved indirectly by the definition of the study area, the scope of the study and the resolution of mapping. Therefore, many systems of land classification link the definition of hierarchical land units to the mapping scale (Christian and Stewart, 1964; Webster and Beckett, 1970; Howard and Mitchell, 1980; Zonneveld, 1995).

Human perception is holistic (McConnell, 1989; Naveh and Lieberman, 1994; Antrop, 1996) and psychological Gestalt-theory describes some laws that explain how we tackle complex patterns. Some laws are very indicative as to how we perceive and react to landscape patterns as well. Fig. 1 illustrates some of these rules. The laws of proximity and similarity of shape (Fig. 1a) show how we group singular elements and create new non-material structures, such as the line suggested by the row of circles. Fig. 1b illustrates the law of vertical dominance; both lines have the same length, but we perceive the vertical one as being longer. Only vertical objects in the landscape keep a constant perspective when viewed from different perspectives. In the landscape, most vertical elements are

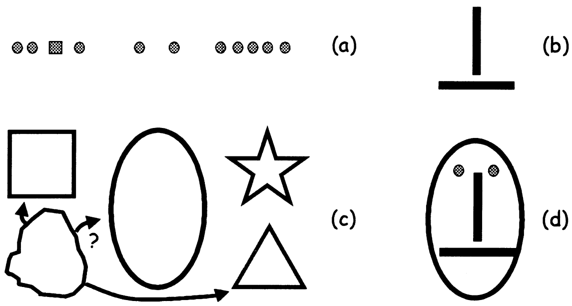

Fig. 1. Some Gestalt-laws and their effect upon describing spatial patterns: (a) law of proximity and similarity in shape; (b) law of vertical dominance; (c) law of the reduction to simple geometric shapes; (d) the whole is more than the sum of its components.

used as landmarks, especially when isolated. Fig. 1c illustrates the law of the simple shape. We try to reduce the complexity of the pattern we see, by transforming irregular into geometric shapes. Finally, Fig. 1d shows that the whole is always more than the sum of its components.

The capability of human perception to recognise and interpret complex spatial patterns demonstrates many of these Gestalt-laws simultaneously. Shapes are simplified and grouped according to similarity and proximity, and wholes are defined. This capability forms the basis of image interpretation, as applied in aerial photo interpretation. The introduction of aerial photography revolutionised our perception of landscapes (Lillesand and Kiefer, 1994) and stimulated the holistic approach to landscape research. In fact, Carl Troll called ''aerial photo-interpretation as a high degree of landscape ecology''. Representation of numerical variables as a map in a GIS often create new types of 'aerial images', which can be studied both as aerial photographs or satellite images. Can the holistic approach be useful in the interpretation of map images of landscape indices? The following case study tries to apply this approach on landscape metrics of a complex suburban landscape.

3. Suburban landscapes

Urbanisation is a complex process that causes profound changes in rural landscapes in the vicinity of towns and cities and creates new and highly heterogeneous landscapes. These changes are diverse and complex, and several models have been proposed to describe the spatial effects of urbanisation (Herbert and Thomas, 1982; Bryant, 1984; Holden and Turner, 1997; Lucy and Philips, 1997). Urbanisation is a world-wide process and with special significance as the urban population is expected to exceed the rural population by 2025 (United Nations Centre for Human Settlement HABITAT, 1996). The landscapes created by the transformation of the countryside around urban centres, referred to as 'suburban' or 'urban fringe' landscapes, and are considered highly dynamic, but remain poorly understood (Lewis and Maund, 1976; Stanners and Bourdeau, 1995; Lucy and Philips, 1997; Stern and Marsh, 1997; Antrop, 1994, 2000).

Concentric models to explain the restructuring of the landscape in the urban fringe are seldom realistic, because the models are based on social and economic parameters and do not consider natural and physical conditions (Bryant et al., 1982). Lewis and Maund (1976) show the importance of accessibility and the transportation network in the urbanisation process. Antrop (2000) proposed a 'sparkling model' to account for landscape changes in the urban fringes. In this model the overall urban condition, transportation facilities and accessibility are important factors. Concepts such as initiators and attractors, features or places that initiate (such as a new road) or attract (such as cross roads) urbanisation processes in undisturbed rural areas, are introduced. Urbanisation also affects the rural landscape as well as the smaller towns and villages in the countryside. These effects are highly dynamic and complex new patterns are created. Patches and corridors are created that are very different from the 'natural' forms commonly studied in landscape ecology. Little is known about the relation between patch and pattern characteristics and the typical urbanisation processes.

4. Study area

This study was done in the province of Eastern Flanders, Belgium, near Ghent. The study area of 240 km^2 is situated the west of the city and extends from the city centre to the countryside, encompassing different types of suburbanised land. Flanders, the northern autonomous region of Belgium, is the most urbanised part of the country with a population density of about 431 inhabitants per square kilometre in 1993. Urbanites represent 97% of the Belgian population (United Nations Centre for Human Settlement HABITAT, 1996), although urban centres are defined and classified according to many criteria: the population density, the multi-functionality of the centre and its sphere of influence, the heterogeneity of the population, and the building density (Van der Haegen, 1991). Belgium contains 15 urban regions with at least 80,000 inhabitants, totalling about 53% of the total population. The main cities are supplements by many large and small towns and heavily urbanised villages. The agglomeration of Ghent, the capital of the province of Eastern Flanders, has 497,771 inhabitants (1997).

Ghent was founded at the confluence of the Scheldt and Lys rivers. The town initially controlled the traffic on the rivers as well and the passage through the alluvial plain, which provided wealth and political importance to the city. Consequently, urban expansion was controlled in part by the natural and physical conditions of the valley and its road network. Access roads ran along sandy ridges on drier grounds and the wet alluvial soils remained grasslands for a long time, even within the medieval walled city. With the start of improvement of the transportation infrastructure in the 18th century, stimulated by the Industrial Revolution and developing trade, urbanisation expanded mostly along the access roads while the valley remained untouched. Suburbanisation of the surrounding countryside started in the 1960s (Van der Haegen et al., 1982) and accelerated with the increased use of private cars. Thus, a complex star-shaped agglomeration was created with intense building along the roads

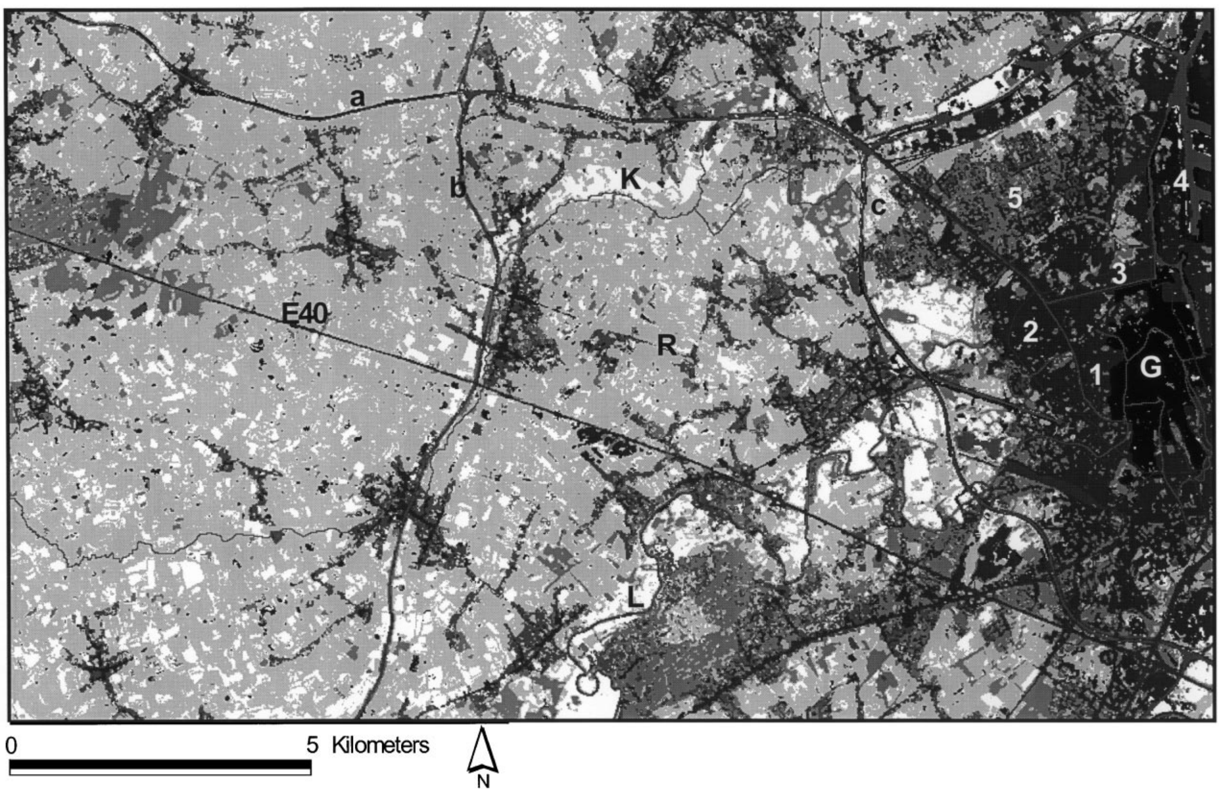

Fig. 2. Land use pattern north-west of the city of Ghent (Belgium), showing the gradient from the historic town center (right) over the (grey shaded) suburban zones of different age towards the countryside (light grey shades). G — historical center, 1 — 19th century expansion, 2 — inner urban fringe, 3 — new economical zones, 4 — harbor, 5 — outer urban fringe; river Lys (L) and Kale (K) and canals (a,b,c); motorway E40 and R railway; gray and black represent build land and some small woods, light grey is cropland and grassland. (Extracted and adapted from the Land Use map of Flanders, Vlaamse Landmaatschappij, OC-GIS-Vlaanderen, 1998).

(ribbon-building), such that surrounding villages and towns became linked by urban strips. Urbanisation is initiated also at a local scale in the connected villages. Most roadsides were built-up with a mixture of residential, commercial and industrial land use, which stimulated traffic congestion. The suburbs are separated by wedges of rural land, wetlands and woods that become loosely connected to the countryside beyond. These areas are affected by significant recreational pressure.

The landscape pattern is extremely complex and fragmented (Fig. 2) with surrounding villages joined in the spreading of built-up land acting as local foci of further urbanisation. Most unaffected rural land exists as small corridors along the river valleys. To improve mobility a new peripheral transportation network (roads, waterways) has been built, which fragments the remaining countryside even more. How can these characteristics be quantified?

5. Methods

The main research question is: do maps of landscape metrics assumed to represent holistic characteristics reveal spatial patterns that correspond to landscape units defined by a holistic approach such as that used in photo-interpretation? Basically two methods were used to classify the suburban landscape based upon patterns formed by land use patches. First, a visual image classification of aerial photographs was made using the holistic ability of human perception to recognise patterns. Second, maps were constructed of landscape metrics computed from the digital land use maps.

The analysis of this study area consisted of the following steps:

1. A holistic landscape classification was made from visual image interpretation of black and white orthophotomaps at a scale of 1:10,000 and additional thematic maps;
2. The land use raster map of Flanders was used to define patches that were used to calculate some common landscape metrics;
3. The cartographic representation of the results and their visual interpretation in relation to the holistic pattern recognition was evaluated;
4. An evaluation was made of the informational properties and the quality of the available digital data layers generally used in planning projects. The focus was on ‘built-up land’, which is considered highly dynamic and significant in suburban zones;
5. The holistic defined landscape units were compared to the maps of the landscape metrics and statistically tested.

To determine the characteristic values for the different landscape metrics for each of the landscape units, the patches defined from the raster map were compared with the landscape units defined holistically. ArcInfo, Arcview GIS 3.1 and Microsoft Access were used for mapping and spatial analysis, and Statistica and SPSS for additional statistical analysis.

5.1. The holistic approach using visual image interpretation

Aerial photography and remote sensing imagery have been valuable tools in a holistic and integrated landscape analysis for a long time (Webster and Beckett, 1970; Daels and Antrop, 1977; Howard and Mitchell, 1980; Dale and Pelletier, 1990; Zonneveld, 1995). Image interpretation can use two approaches (Lillesand and Kiefer, 1994). Image classification is mostly applied on numerical images to classify the pixel values into categories with logical and statistical algorithms. Visual image interpretation is a non-numerical approach starting from the image characteristics perceived on a screen or hard copy. The pre-processing and enhancement of the image is important, because they direct the interpretation. Thematic mapping can be considered as a form of pre-processing and enhancement. According to Lillesand and Kiefer (1994), basic characteristics of the image used during visual interpretation are shape, size, pattern, tone or hue, texture, shadows, geographic or topographic site and associations between features and identified objects.

5.2. The analytical approach using landscape metrics

The description of landscape characteristics related to spatial patterns and the prospects for their quantification has become an important topic in landscape ecology (Turner and Gardner, 1990; Turner et al., 1990, 1991). The wide variety of landscape metrics or indices (Martinez-Falero and Gonzalez-Alonso, 1995; Farina, 1998) has lead to a discussion of their actual significance (Fry, 1998). Dramstad et al. (1998) state that the use of landscape indices is necessary, albeit controversial, with the increasing need for quantitative assessment of impact and change. The purpose of quantitative landscape indices is twofold: (1) to be additional attributes for classification of landscape types or regions; and (2) to be indicators of landscape changes and disturbances (Dramstad et al., 1998). Burnside et al. (1998), Nakagoshi et al. (1998) and Nomura and Nakagoshi (1999) give other examples. However, the potential for such quantitative analyses depends fundamentally on the availability of geographical data, especially from maps. The continuous, complex and heterogeneous character of most landscapes makes the use of spatial sampling necessary (Bunce, 1984; Hunsaker et al., 1994).

Different landscape metrics are recognised although no generally accepted classification is available. Two types were used here: the first measures patch characteristics, such as size, shape and edges. A second deals with the spatial arrangement of adjacent patches and needs an aggregating spatial context to be calculated.

The choice of landscape metrics also depends on the nature of the data from which they are calculated. In this study, the digital land use map of Flanders was used. Raster maps, such as the land use map, do not have a topology that allows working with objects such as patches. Patches need to be defined by aggregating adjacent pixels of the same land use category. This was performed by the Region Group procedure of the Spatial Analyst in Arcview GIS 3.1 with the diagonal option for grouping. The resulting patches have jagged edges formed by the 20-m pixel size.

The following landscape metrics were selected: patch area; corrected perimeter-area shape index; two forms of the Shannon entropy and the fractal dimension.

The patch area and perimeter are easily calculated measurements from which many other landscape metrics can be derived. The distribution of the patch area gives an initial assessment of spatial heterogeneity and scale of analysis. The accuracy of the patch area and perimeter calculation depends on pixel size and grouping method. A more accurate analysis of these variables insures more reliable interpretation of landscape metrics based upon area or perimeter.

The corrected perimeter-area index (CPA), a measure of patch shape, is defined as $\mathrm{CPA}=(0.282P)/A^{0.5}$, where P is the perimeter of a patch and A its area (Farina, 1998). The index varies between one for the most compact shape of a circle and becomes infinite for a line (theoretical the most elongated shape).

The fractal dimension, D, was used to express the irregularity of the borders of the patches (Burrough, 1986; Milne, 1990; Farina, 1998). The fractal dimension D was determined as the slope of the regression of log (patch perimeter) on log (patch area).

The Shannon entropy was used as an indicator of the combined diversity of categories and complexity of the spatial pattern formed by the patches. The calculation of Shannon's formulae needs integration over a sample area. Determination of the entropy for the whole study area is meaningless as no spatial variation of the entropy can be mapped. Mostly quadrant sampling is used to reveal spatial variation of landscape indices (Turner et al., 1990; Nakagoshi et al., 1998). For this study quadrants of one square kilometre were used according the Belgian metric coordinate system (Lambert 72), which is also used to aggregate and to map environmental indices. It should be noted that biological inventories use also a one-kilometre square quadrant system that is slightly translated to the national system. Because entropy indices integrate information between spatial units, here quadrant blocks, the integration requires careful thought (Stöcker and Bergmann, 1978; Antrop, 1998). Shannon's formulae, which are used frequently in landscape ecology to calculate landscape diversity, were initially used in information theory as a measure of the neg-entropy of information entropy, expressing the amount of information contained in a series of signs. The distributive entropy summarises the proportional area of each patch within the aggregating spatial unit, while the summed entropy summarises the proportional area of each land use category. Because each patch is defined by a difference in land use, entropy depends on both the diversity of land use categories and spatial fragmentation.

5.3. Visualisation by thematic mapping

Visual image interpretation typically results in a vector-type thematic map. The results of quantitative analysis of raster maps can also be visualised using thematic maps. Visualisation of quantitative variables in thematic maps can be achieved in many ways and the result is determined largely by the classification method (Arnberger, 1977; Unwin, 1981). Thematic mapping of landscape metrics results in particular chorochromatic choropleth maps showing areas of equal value according the classification method (Burrough and McDonnell, 1998). These maps can be considered images that represent landscape metrics. Once more, visual interpretation is used to evaluate the patterns. Pattern shape and size, patches formed by tone or hue that represent the quantitative classes of the landscape metric, as well as regularity and repetition are used in the evaluation.

Table 1
Landscape types

Code	Description
1	Urban centre: dense housing without gardens
2	Inner urban fringe: dense housing with gardens
3	Outer urban fringe: open housing with gardens
4	Village+plane spreading of new housing
5	Industrial corridor and harbour
6	Village+linear spreading along the access roads
7	Ribbon-building along the roads
8	Undisturbed valleys
9	Countryside with woods
10	Rural countryside with scattered settlement

6. Results

6.1. Mapping landscape types and metrics

The visual image interpretation recognised 10 types of landscapes related to suburbanisation (Table 1) and 66 landscape units were mapped (Fig. 3).

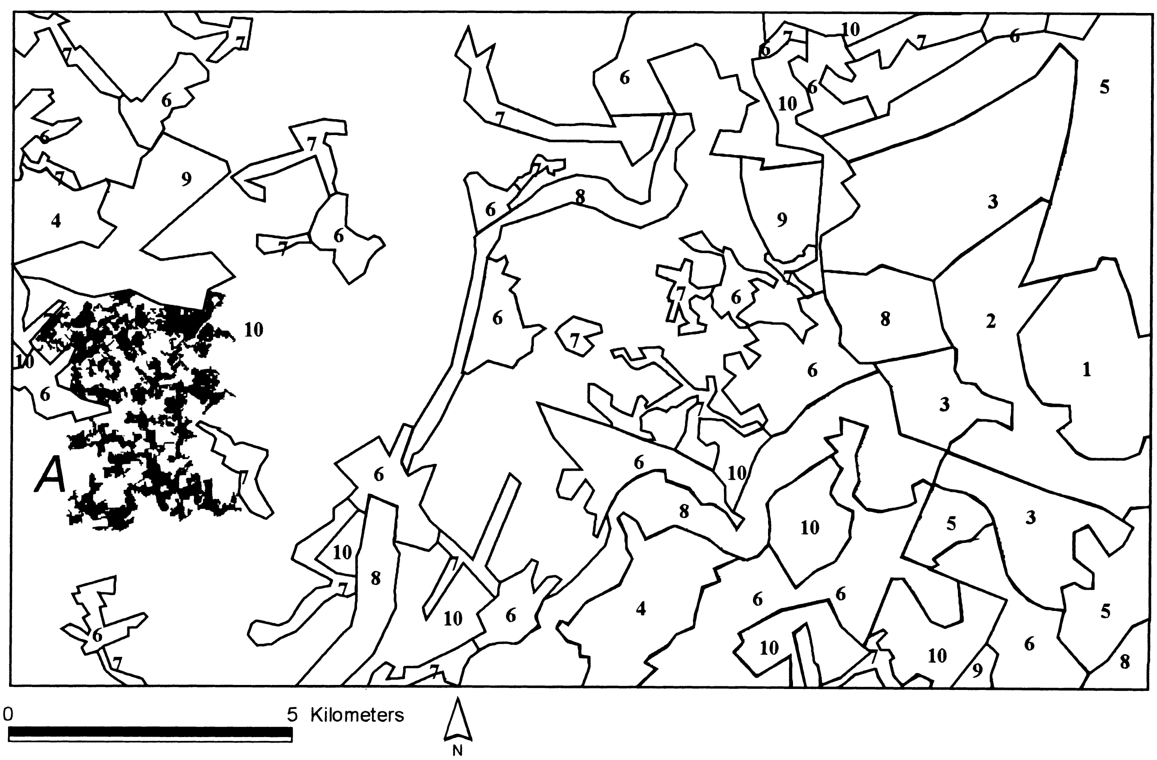

Fig. 3. Landscape zones interpreted from aerial photographs and additional thematic maps. Numbers refer to landscape type as in Table 1. One black irregular patch is marked for further evaluation.

Land use patches were defined from the digital raster map of the land use of Flanders. This map is based on a supervised classification of Landsat 3 TM imagery from August 1995 and was enhanced with overlays of other thematic maps, such as CORINE Land Cover data and transportation infrastructures. Thus, the classification accuracy was improved substantially. However, basic data have a raster format with a pixel resolution of 20 m. About 20 different land use categories were recognised, including continuous urban fabric, discontinuous urban fabric, urban fringe/green area, industry/commercial, infrastructure, harbour, airport, mineral extraction sites, highway, regional way, arable land, grassland, maize/tuberous plants, alluvial grassland, orchard, deciduous forest, coniferous forest, mixed forest, parks/gardens, heath land/bare soil, beach/dunes, mud flat, navigable waterway, non-navigable waterway, estuary, and sea.

For the study area of 240 square kilometres, 39,969 patches or about 167 patches per square kilometre were distinguished. Area and perimeter were calculated for each patch for the calculation of different landscape metrics.

First, a simple classification was made of the area of each of the patches. Mapping patch area, although seemingly trivial, is difficult when many small patches need to be represented, as their size hinder the construction of a clear coherent image. Fig. 4 represents the result of an equal area classification of the patch area using five classes represented in grey shades. The equal area classification maximises the information in the map. The patch area varies from 400 m^2 determined by the pixel size of the land cover map to

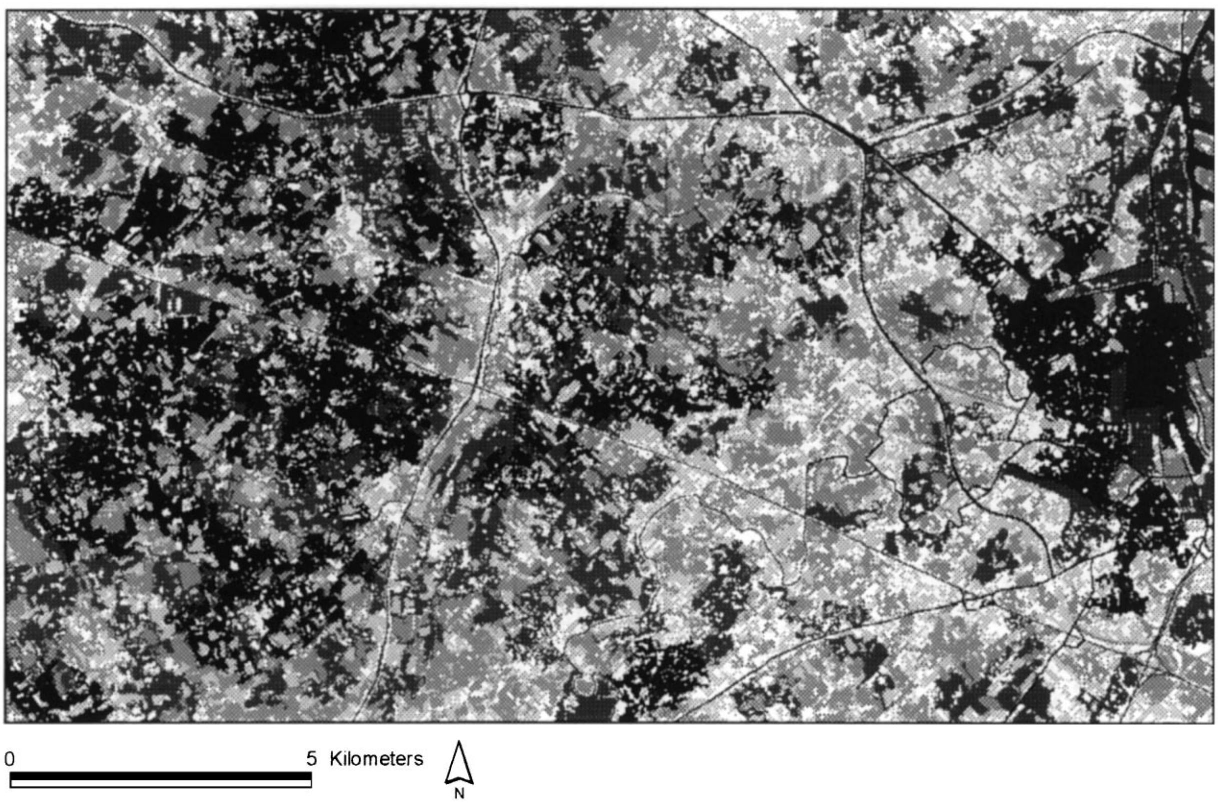

Fig. 4. Patch area of land use types. Equal area classification using five classes: large patches are black; small ones light grey. Roads and waterways have been overlaid. Note the concentration of small patches in the outer urban fringe, in the valleys and along the access roads. Small patch areas indicate severe fragmentation in the landscape. Both in the inner urban fringe and urban core as in the countryside larger patches are found, but belong to completely different landscape types.

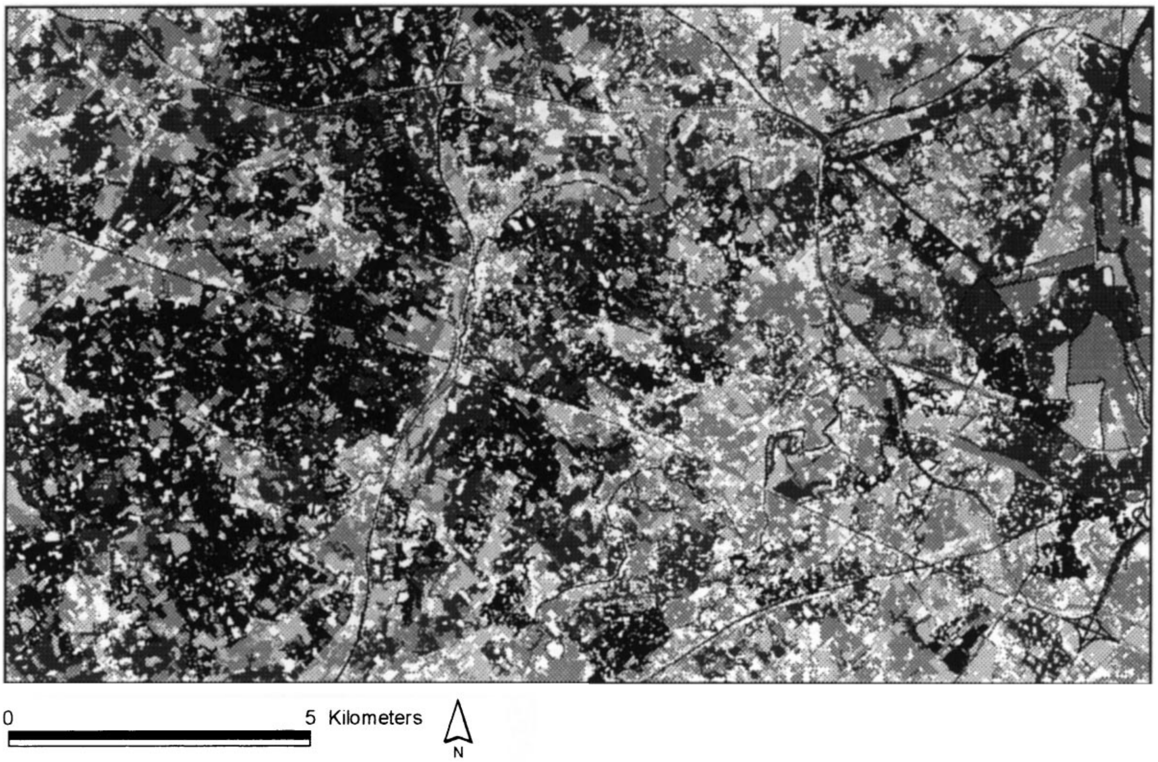

Fig. 5. CPA shape index of landscape units: small values (light grey) indicate compact shapes, high values (dark grey) elongated shapes. Roads and waterways have been overlaid. The small patches of the outer urban fringe and in the valleys as well as along the roads appear to be more compact. Highly elongated patches are found both in the inner urban fringe and in the countryside.

4.70 km^2. This thematic map reveals the concentration of small patches (light and medium grey) in the valleys, in the outer urban fringe, and along the roads with ribbon-building, illustrative of severe fragmentation. Larger patches occur in the inner urban fringe, urban core and the countryside, but belong to completely different landscape types.

The CPA, ranging from 1.128 to 18.437, was also mapped in five classes using the equal area method (Fig. 5). The small patches of the outer urban fringe and in the valleys as well as along the roads appear to be more compact. Highly elongated patches are found both in the inner urban fringe and in the countryside.

Fig. 6 shows the map of the fractal dimension using five equal area classes. The fractal dimension varies between 1.28 for the most regular patches to 1.66 for the most irregular patches. The low fractal dimension values in the completely built-up areas in the urban core and industrial zones, as well as in the large woods and in some parts of the valleys, indicate more regular and straighter patch borders. Agricultural zones are characterised by high fractal dimension values and the urban fringes by medium values.

Fig. 7 gives the distributive and summed information entropy for the visually interpreted landscape units. Although the entropy values of the distributive (HD) calculation differ from those of the summed (HD) calculation, a correlation coefficient of 0.48 (significant at $p<0.05$) (Table 2) indicates that the apparent observed difference between the maps is due largely to the choices of classification and shading. The summed entropy (HS) varies between 0.20 and 0.44, the distributive entropy (HD) between 1.80 and 10.00. The summed entropy (HS) of the land-use map shows high values in the outer urban fringe and in zones dissected by rivers, canals and roads, and around village centres. These values indicate a large variety (diversity) of land use. The distributive entropy (HD)

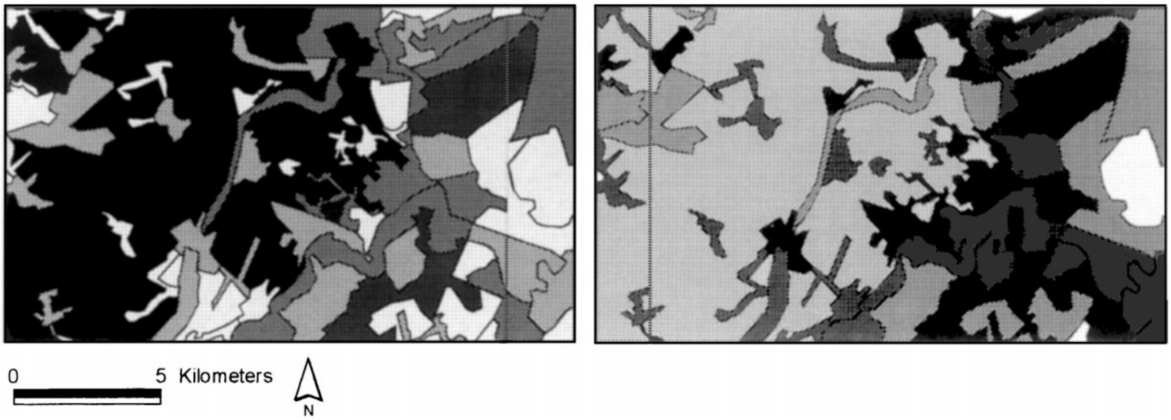

Fig. 6. Shannon information entropy calculated for each visually mapped landscape unit. Distributive entropy (HD, left) and summed entropy (HS, right). Light grey: low entropy, black: high entropy.

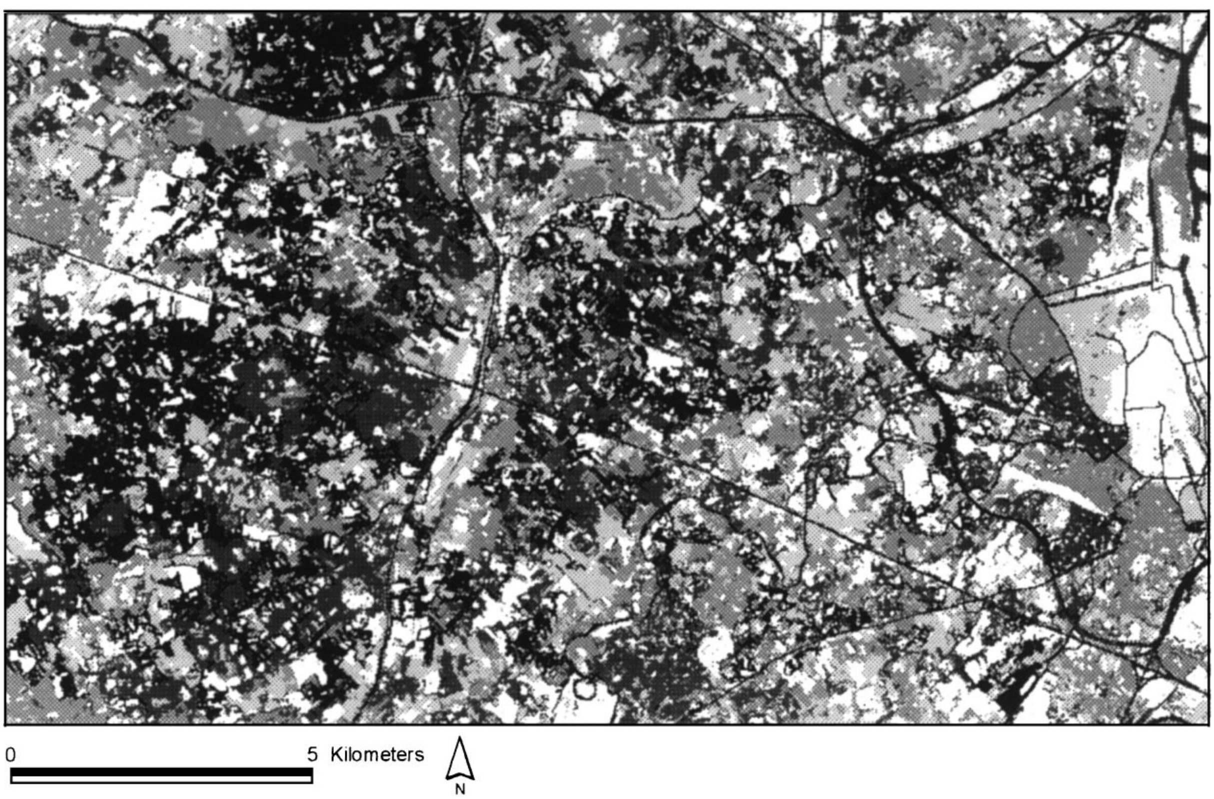

Fig. 7. Fractal dimension of the land use types: low values (white and light grey) indicate regular and 'straight' boundaries, high values (dark grey) are irregular 'twisted' boundaries. Roads and waterways (black) have been overlaid.

Table 2
Pearson correlation coefficients between landscape metrics (average patch area, average shape index CPA, average fractal dimension D, distributive (HD) and summed (HS) entropy) and the percentage built-up area for 66 landscape units

	Built-up (%)	Average patch area	Average CPA	Average fractal D	Entropy HD
Average patch area	0.100				
Average CPA	−0.009	0.80[a]			
Average fractal D	0.200	0.07	0.39[a]		
HD	0.097	−0.06	0.07[a]	0.39[a]	
HS	0.191	−0.43[a]	−0.43[a]	0.37[a]	0.48[a]

[a] Correlation is significant at the 0.05 level two-tailed.

combines variety of land use categories and their spatial fragmentation into smaller patches. Low values in the urban centre and inner urban fringe are common in both maps and indicate large areas of few land use categories, mainly built land. For the countryside and outer urban fringe and valleys, both maps seem complementary.

6.2. Comparison and spatial classification

Pearson correlation coefficients were calculated between the landscape metrics characteristic for each landscape unit defined by the holistic landscape classification. Within each landscape unit the average values of patch area were calculated, as well as the patch shape index, CPA, and the average fractal dimension, D, of the patches, the distributive (HD) and summed entropy (HS) and the percentage of built-up land (Table 2). Landscape metrics such as the patch area, the shape index CPA and the fractal dimension D also characterise each patch separately and were compared as well. Only the fractal dimension displays normal distribution, patch area and shape are skewed and have a Poisson-like distribution greatly affected by outliers. As the shape index CPA is based upon area and perimeter of the patches, both indices correlate strongly (Table 3).

Table 3
Pearson correlation coefficients between a random sample of individual patch characteristics: patch area, shape index CPA and fractal dimension D (N=11 852)

	Patch area	CPA
CPA	0.600[a]	
Fractal D	0.048[a]	0.336[a]

[a] Correlation is significant at the 0.01 level two-tailed.

Table 4
Breakdown analysis of the landscape metrics using landscape type as a grouping variable[a]

Landscape index	F-Value	p-Level
Number of patches	0.6265	0.7695
Average patch area	2.0054	0.0556
Average CPA	1.5743	0.1456
Average fractal dimension	3.3442	0.0025[b]
Distributive entropy, HD	2.39279	0.0227[b]
Summed entropy, HS	14.9931	0.0000[b]
Built-up (%)	30.2485	0.0000[b]

[a] F-value and p-level from the analysis of variance are given calculated upon 66 landscape units, which were also used to calculate the averages.
[b] Significant at the 0.05 level.

With the landscape types (Table 1) as a grouping variable, the number of patches, the average patch area, and average CPA proved insignificant (Table 4), while fractal dimension and entropy indices were significant. In particular, the summed entropy (HS) proved to be useful to characterise the visually defined landscape units, as evident in a comparison of Figs. 2, 3 and 6. The high F-value (F=30.249) of the percentage built-up land indicates the relation of the landscape types with the urbanisation process.

7. Discussion

7.1. The influence of data quality and processing

Data quality of digital map layers is crucial for spatial analysis. According to Burrough and McDonnell (1998), important criteria to evaluate data quality are actuality, completeness, consistency, accessibility, accuracy and precision (also related to raster map resolution and the degree of detail) and sources of errors caused by data entry and manipulation. The general available data layers in this analysis differed greatly in several of these criteria. The actuality of the land use data in highly dynamic suburban landscapes is particularly important. Aerial photography and remote sensing are appropriate tools for updating land cover maps. A limiting factor in satellite imagery is the spatial resolution compared to the highly fragmented spatial structure of suburban landscapes, which results in a large proportion of mixed pixels and accordingly poor classification accuracy. Large-scale aerial photographs are more appropriate, but necessitate a more elaborate interpretation to obtain digital thematic data layers. However, obtaining detailed thematic information about land cover is not a purely technical matter, but also implies important conceptual aspects. For example, determining and monitoring the area of built-up land is a primary task in the study of urbanisation processes. Is built-up land defined as a field parcel containing a building, or as the footprint of actual buildings? How do we define a building? Must it have solid foundations or can it simply be a structure on the ground? How do we differentiate these upon remote sensing images? The following example shows the severity of the problem in densely built-up areas. Fig. 8 compares different inventories of the built-up land in a suburban

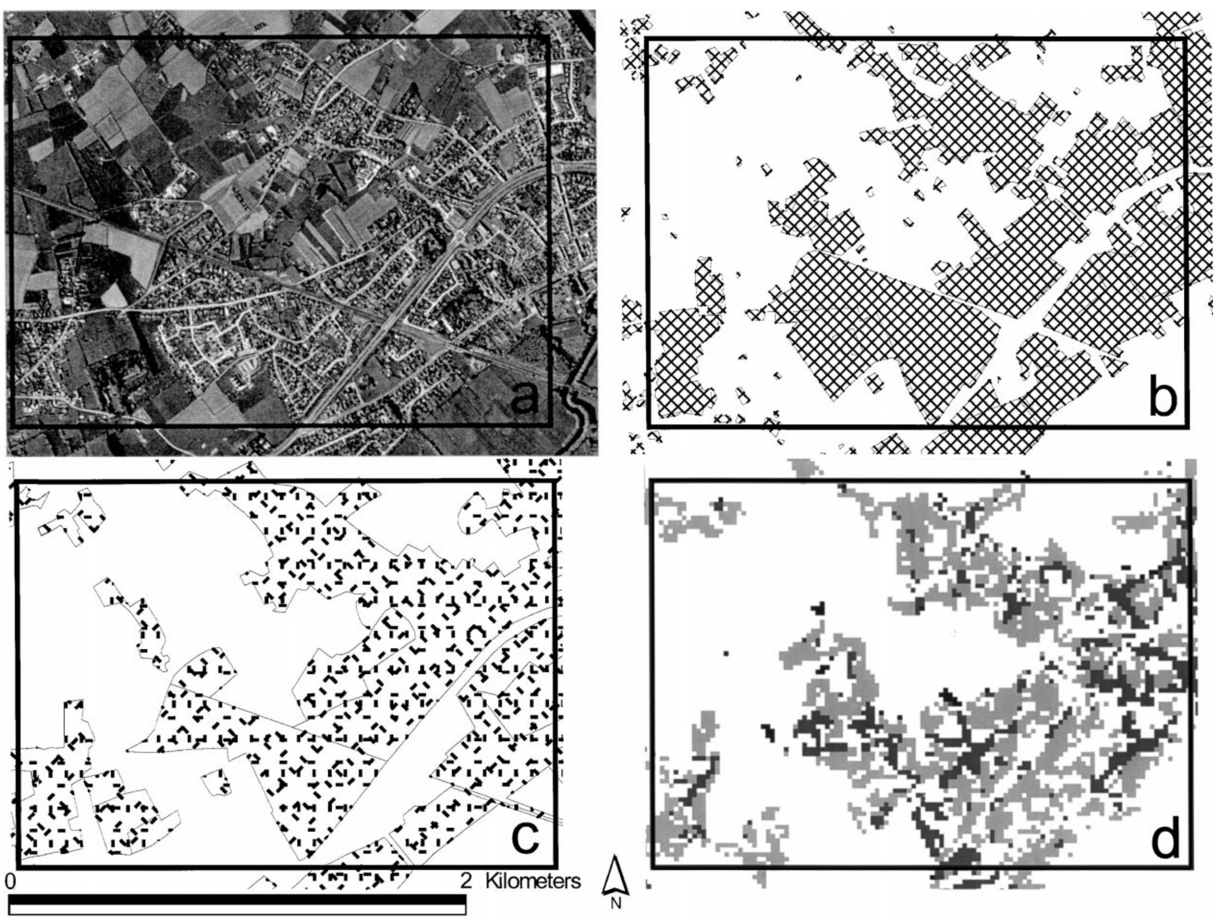

Fig. 8. Comparison of inventories of built-up land in suburban zones: (a) orthophotomap 1995; (b) manual digitalisation of the footprints of buildings and construction by interpretation of the orthophotomaps; (c) built-up land according to the biological evaluation map (digital version 1997); (d) built-up categories defined by supervised classification of Landsat 3 TM data 1995.

zone with an orthophotomap (a). The inventory made by the Province of Eastern Flanders (b) is based upon the interpretation of these orthophotomaps and represents the manually digitised footprints of whatever construction can be detected on the image. Digitisation errors are clearly visible. The inventory of the biological valuation map of Flanders (c) defines built-up land as the whole field containing any type of building. This inventory clearly exaggerates the built-up appearance of the landscape and is least concordant with the aerial photographs and satellite data. The result of the supervised classification of Landsat TM imagery, which was used for the patch definition, is given in (d). Densely built areas are black and a gradation of more open housing with gardens is grey. When compared to the orthophoto, the satellite map shows that mixed pixels cause significant differences in category assignment, as well as in spatial delimitation between built-up and non-built-up land.

The information from raster images is unstructured in objects and the classification includes much uncertainty (Canters, 1997). The land use map created from the classification of satellite data necessitates the grouping of similar adjacent pixels to define landscape patches, which are used to calculate basic variables, such as area and perimeter. This was done with the RegionGroup procedure including diagonal pixels of the Spatial Analyst of ArcView GIS 3.1. The result is surprising as illustrated by the huge irregular patch marked (A) in Fig. 3. Such outliers greatly affect further statistical analysis and classification in thematic maps. In this circumstance the significance of the calculated landscape metrics need to be checked individually.

7.2. *Interpretation of the landscape metrics*

Mapping of landscape metrics, particularly those in heterogeneous suburban landscapes with a complex transition from pure urban to rural countryside, poses different problems. Because landscape metrics represent both an abstraction of nature and the content of the patches formed by land use, mapping these indices creates patterns that are not always easily interpreted.

Patch area is an attribute and not a genuine index. It is not normalised and not straightforwardly applicable when compared to descriptive statistics such as average and variance. Mapping the thematic classification of the patch area enhances the heterogeneity of the landscape (compare Figs. 2 and 4) and is useful when many small patches are involved whose individual size is indiscernible in the image. The depiction of a limited number of classes in the thematic map may enhance new patterns of zones with large and small or mixed size patches that can be compared to the main suburban structures of the landscape as given by the visually-defined holistic landscape units. In our study of Ghent, the outer urban fringe is clearly distinct by an aggregation of small patches. However, the method of thematic mapping largely determines the outcome; the choice of the number of classes and the classification methods are essential. An attribute such as area, represented in a choropleth map, is sensitive to area and size dependencies (Unwin, 1981).

The CPA ranges from one for the most compact shape (a circle) to infinity for a line. Fig. 5 presents a complex image that demands careful interpretation. The urban agglomeration depicts zones that belong to the same classes of medium to high CPA (more elongated patches). The inner urban fringe has the highest CPA, although high CPA also occurs in some agricultural zones in the countryside. Valleys and the outer urban fringe have low CPA. The similarity of CPA between dense urban housing and some field structures indicates that CPA should be combined with other indices to allow better interpretation.

Linear landscape elements have a great influence in the spatial delimitation of patches (Fig. 6). Consequently, breaks in fractal dimension classes frequently occur along roads, rivers and canals. Although significantly correlated to CPA, the fractal dimension D generates very different patterns. The fractal dimension D is more normally distributed than CPA. It reveals the importance of the long straight borders of roads and railways. The urban centre yields low fractal values, while more open housing with gardens in the suburbs show more irregular bordered patches with higher fractal dimension. The outer urban fringe and river valleys are characterised by medium values in fractal dimension (medium greys), while in more rural areas a higher contrast between patches with low (light grey) and high (dark grey) fractal dimension can be seen.

The Shannon information entropy integrates the diversity of the patch ‘content’ with spatial pattern. The Shannon index depends largely on the definition of aggregating spatial units that are dependent for its calculation and also on the calculation of the proportional occurrence of patches. The distributive entropy is more sensitive to spatial fragmentation than the summed entropy. However, the summed entropy is more closely related to the holistically defined landscape types. The summed entropy combines qualitative (land use types) and quantitative (fragmentation) properties of predefined spatial units. Although the percentage of built-up land is closely associated with the visually defined landscape units, the correlation between entropy and the percentage built-up land is insignificant owing to the uncertainty of land use classification from remote sensing data, combined with the algorithm used to define patches by pixel grouping. The Shannon entropy proved to be useful also to monitor structural changes from rural to urban landscapes with detailed land use maps (Antrop, 1998). Our results indicate that Shannon entropy is an interesting landscape metric for typology of suburban landscapes as well.

The differences between the maps of landscape metrics and that of visually-defined landscape units is the result of the great sensitivity of the landscape metrics to data quality and occasional the extreme effects of the computational algorithm. Visually-defined units are based on holistic properties of perception that automatically resolve noise caused by data quality and that neglect the outliers that affect quantitative classification methods. Because land use categories share similar metric patch properties, quantitative landscape indices can not distinguish between categorical different landscape units. As the Shannon entropy accounts for land use diversity, and also gives the best comparison with the visual classification of landscape units.

8. Conclusions

Visual image interpretation of remote sensing imagery offers an efficient method to classify complex and heterogeneous landscapes and spatial units with image pattern characteristics. These landscape units can be used as aggregating areas to calculate landscape metrics of patches generated by automatic grouping procedures in GIS. Full understanding of how the index values are obtained is necessary, including the precise index definition of their calculation their sensitivity to data quality. Basic landscape indices include area, shape and fractal dimension. Entropy calculation needs a spatial unit of integrating zone, such as holistically-defined landscape units. Average patch indices can be added in the same way. Although landscape indices correlate statistically, their mapping can reveal different patterns. The use of patches restricted to the metric properties of land use does not yield sensible landscape typology nor classification of highly heterogeneous landscapes, such as those in urban fringe zones. This requires the qualitative attribute of the land use category. The summed entropy fits the visually defined units most closely and integrates a diversity of land use types with the fragmentation of patches.

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Marc Antrop is a geographer at the University of Ghent, Belgium and head of the Department of Geography. He specialises in regional geography and landscape science, using techniques of field surveying, aerial photography, remote sensing and GIS. His research focuses upon processes of change and transformation of landscapes, in particular the cultural landscapes of Europe. He lectures landscape geography (chorology and typology), landscape ecology, landscape architecture and spatial and environmental planning. He is promoter and author of the atlases of the relics of the traditional (cultural) landscapes of Flanders, which form now one of the basic documents for the planning policy. He is vice-president of the Royal Committee for Monuments and Landscapes, in charge of landscape protection in Flanders.

Veerle Van Eetvelde is a geographer and planner. She specialises in GIS and spatial data structures. At present, she is a researcher at the Department of Geography of the University of Ghent. She is co-author of the landscape atlases, is active in studies for environmental impact assessment related to landscape. At the moment, she is undertaking research to set up an integrated monitoring system for the Flanders region where landscape ecological processes should be related to changes of the biodiversity.