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RESEARCH ARTICLE

Measuring the compactness of European medium-sized cities by spatial metrics based on fused data sets

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The main objective of this article is to compare European medium-sized cities in terms of compactness. Both existing and new metrics are used. The metrics are based on the fusion of recently available European-wide data sets with common standards for all countries. The fused data used in specific are Urban Atlas and Urban Audit. One source of inspiration of new metrics is landscape ecology, but the analogies are not always straightforward. The method is applied to a large number of cities. It is found that the combination of existing metrics with those newly proposed is able to adequately describe compactness and its components.

Keywords: spatial metrics; urban sprawl; compact city; Urban Atlas; Urban Audit

1. Introduction

Cities are a reflection of individual, social and political choices. They develop and expand based on a myriad of decisions (Batty 2008). Clearly, while citizens make decisions based on assessing their own private costs and benefits, public costs and benefits follow (Wassmer 2000). In a largely non-cooperative game, each player chooses a residence location to optimise his personal rather than the society's benefit, resulting in a Nash equilibrium. Individuals definitely consider the positive and negative externalities of their candidate location due to the surroundings (Ewing 1994). They do not bear, however, the public cost of their decisions, and sometimes, they might ignore it (Ewing 1994). Most agree that urban sprawl is a case where personal decision-making has high social costs and action at the policy level is needed.

Urban sprawl is the opposite of urban compactness. While urban sprawl and urban compactness are antonyms (Chin 2006, Besussi *et al.* 2010, Mubareka *et al.* 2011), urban sprawl and urban growth are not synonyms. Urban sprawl is a type of urban growth but not the only one. Specifically, urban sprawl is a type of excessive and unplanned urban growth (Razin and Rosentraub 2000). The problem of sprawl is not growth *per se*, but rather that it is a specific type of dysfunctional growth (Ewing *et al.* 2002). Therefore, limiting sprawl does not necessarily imply limiting growth but merely setting rules to it.

Sprawl is a non-compact, low-density development urban form, often exhibiting scattered, leapfrog, strip or ribbon structure, resulting in poor travel patterns (Ewing 1994, Wassmer 2000). Sprawl can take the form of single-use bedroom communities

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(Schneider and Woodcock 2008). It can also take the form of parasitic retail development along the street network and near highway exits, attracted by increased accessibility (Torrens 2008). A key observation is that the linkage between different land uses is poor due to excessive segregation (Ewing 1994). This definition of accessibility, the one related to the mix of uses, is more efficient compared with the sometimes-proposed overall accessibility of an area based on the street network, regardless of land use, such as the fractal dimension of the road network or the distance to the Central Business District. Despite the fact that it encapsulates the notion of decentralisation, sprawl is not the only alternative to monocentric development. Polycentric development, for example, can be both decentralised and compact. Moreover, because sprawl is a process in time, sometimes it is described as a temporary condition (Frenkel and Ashkenazi 2008). But this can only be true if suburbanisation occurs within planned areas. Otherwise, unplanned sprawl has the further side effect of undermining future planning by establishing an irreversible *status quo*. In that case, sprawl might as well be a temporary condition but in the wrong direction. After the infilling, it results into an inefficient urban structure.

Most but not all scientists agree that sprawl should be curtailed. Some question that compactness is either desirable or feasible as a goal (Breheny 1997, Gordon and Richardson 1997, Neuman 2005). Recent advances in telecommunications certainly add an additional centrifugal force (Gordon and Richardson 1997) although their impact might be exaggerated (Ewing 1997). At the European Unions' policy agenda, however, urban sprawl is clearly considered parasitic (Torrens 2008) and is explicitly mentioned as a problem. Sprawl is seen as a product of market economy dominance, or laissez-faire, that needs to be controlled. It should be redirected via smart growth and combined with polycentric urban planning to strengthen territorial cohesion (CEC 2006b). Smart growth redirects development to unused spaces within the urban footprint rather than limiting it (Ewing *et al.* 2002). Sprawl in Europe is clearly a significant trend but is often neglected (CEC 2006b). French cities, for example, have doubled their footprint in just 15 years (Kasanko *et al.* 2006). However, the rates in different member states are diverse. The variation increased further after the enlargement that took place during the past decade to include several former communist countries in Central and Eastern Europe, with distinctively different planning systems and land markets.

Sprawl is acknowledged to have several negative impacts in European Unions' territory. It contributes to high and unsustainable energy consumption rates because of increased levels of private transport (CEC 1999, 2011a) and heating demands (CEC 2006c). Increased energy demands result in air pollution and, given that urban centres are the primary source of greenhouse emissions (Grimm *et al.* 2008), decreased resilience to climate change (CEC 2008). Apparently, CO_2 emissions negatively correlate with urban densities (CEC 2006b). At a political level, the higher energy demands also increase the dependence of European Union and its member states on oil-producing counties. Sprawl threatens cultural assets and landscapes and degrades the countryside (CEC 1999, 2011a). It is a land-consumptive pattern (Wilson *et al.* 2003), and soil is a non-renewable resource (CEC 2006b). By increasing soil-sealing, it results to fragmentation or loss of natural habitats (biotopos) and ecological corridors (CEC 1999, 2006c, 2011a). Increased land consumption is also associated with the loss of prime farmland (high-quality arable land) and results in conflicting land uses (CEC 1999, 2010). It makes provision of infrastructure and public services more costly (CEC 1999). Sometimes, because the costs cannot be met, infrastructure is missing, degrading both the environment and the quality of life. Other effects of sprawl are also investigated such as its association with social equity (Burton 2000). Investigated associations also include that to obesity

(Burgoine *et al.* 2011), to social isolation of kids playing video games alone instead of socialising outdoors (Will 1999) and to the psychological costs imposed to family members not driving a car (Ewing 1994).

To limit such consequences the compact city is set as a goal in the European Union. The properties of the compact city are explicitly defined as minimal land consumption, short distances or minimising transport, high density and mix of land uses (CEC 1999, 2006c, 2007, 2010). Strong control of land supply and speculative development is applied to meet only justifiable needs for growth (CEC 2007). A strong argument put forward in favour of the compact city in Europe is that cities face stable or recessive demographics. Therefore, new suburban growth in general cannot be attributed to demographic pressure. Nonetheless, sprawl exceeds population growth for a number of reasons including the declining quality of life in city centres. It is also driven by the increasing prosperity of European Union's citizens fuelling the demand for second homes, sometimes resulting to 'weekend towns'. In some places, sprawl is also linked to increased seasonal population, for example attributed to tourism.

A second strong argument in support of the compact city is that sprawl is not justified unless available space within the cities is used first. Using means reusing as well. It is estimated that the extent of the derelict industrial sites in Europe is higher than that of the total area of greater London (CEC 1999). In that respect, policies against sprawl are often coupled with ensuring rational use of soil and with recycling land. Urban regeneration, the reuse of brownfields (empty industrial sites) and greyfields (empty shopping malls) are currently promoted and subsidised.

In order to be able to monitor cities, data sets have to become available. At the global scale, while census data can relatively easily be found, existing data sets regarding land use and city data are very rare (Schneider and Woodcock 2008). The European Commission has recognised the need to create urban and regional data sets with comparable information amongst member states. It has also recognised that urban statistics and comparative indicators at the European level have to be produced in order to be able to compare and benchmark cities (CEC 2008). However, data scarcity remains a problem today. For most cities in Europe, it is hard to find suitable data. Data sets suitable for cross-European comparison of cities are even harder to find. Consequently, it is not surprising that cross-national comparisons of urban form are scarce (Huang *et al.* 2007). In fact, the only two data sets with European-wide coverage available for cities, in common standards, are Urban Atlas and Urban Audit. CORINE land cover data set is also provided by the European Commission starting from 1990. But this is a coarse data set, at a scale of 1/100.000, suitable for metropolitan areas only. It is definitely not suitable for medium-sized cities typically requiring a scale of 1/10.000. Also CORINE's classification system does not include any direct information regarding urban land uses.

Frequently the only viable solution to obtain spatial data is to resort to earth observation. In fact, currently the only source for approximately knowing the extent of cities globally is remote sensing (Schneider *et al.* 2010). Its advantage as a data source for monitoring sprawl is that it yields comparable results in different parts of the globe since it is a relatively objective method. Independence of local data is even more important given that the overwhelming proportion of urban growth will take place in developing countries (Huang *et al.* 2007) where information is scarcer. Large areas can be covered with high spatial and temporal frequencies. Remote sensing has been used in order to compare the growth of cities in different parts of the globe (Schneider and Woodcock 2008), in single-city studies (Herold *et al.* 2002, 2003, Wilson *et al.* 2003) as well as in cross-border areas (Davis and Schaub 2005).

An often neglected problem however has to do with the accuracy with which urban areas can be extracted from satellite imagery. Urban areas are hard to be separated from the other features of the image. Urban areas are especially mixed up with barren land due to similar spectral signatures (Davis and Schaub 2005, Stathakis *et al.* 2012, Stathakis and Faraslis 2014). The presence of barren land, or the absence of vegetation, varies significantly in different places of the globe. Therefore, the extraction of urban areas is sometimes trivial, when cities are surrounded by vegetation, but other times hard. As a result, in some studies the classification error is comparable to the percentage of change in decade. This problem is also propagated to vector land cover data sets since they also typically rely heavily on remote sensing as the primary information source. CORINE land cover, for example, is a product of manual photointerpretation of LANDSAT imagery, with nominal acceptable thematic error of 15% or 85% accuracy (CORINE 2000). This in turn means that apparent sprawl percentage values up to 15 might in fact be attributed to error, not to actual changes on the ground.

While the need for relevant data sets is starting to emerge in European policy documents, the need for operationalisation of sprawl, as Ewing *et al.* (2002) put it, is almost completely missed. That is, sprawl has not been represented by variables that can be objectively measured in order to be able to empirically be studied. Operationalisation is, however, a prerequisite for comparing between cities as well as for comparing with theory (Herold *et al.* 2003). It is impossible to set tangible goals and monitor policies without it. Operationalisation is not an easy task. Methods used in the literature, in different countries, are highly variable and difficult to compare and synthesise. As Torrens (2008) vividly puts it, different lenses are used to study sprawl since methods are data-driven rather than based on theory. Nonetheless, the inability to measure urban phenomena means that the processes involved are not fully understood. This is a barrier to improving the theories used to describe them (Longley and Mesev 2000).

In any case, operationalisation appears to involve four relatively distinct steps. The first step is to select the main characteristics or dimensions of sprawl and their attributes to be captured. The second step is to select specific metrics that correspond to the attributes in order to quantify them. The third step is to check for correlation between metrics to identify redundant ones. And finally, the fourth step is to find a way to combine the metrics in order to provide a ranking or a classification or a comparison of cities.

A main observation involved in the first step is based on the fact that the dimensions of sprawl are definitely multiple. Density is almost always selected as one (Razin and Rosentraub 2000, Burton 2002, Frenkel and Ashkenazi 2008). This is because density is relatively easy to compute, and its physical explanation is straightforward since sprawl is typically characterised as a low-density phenomenon (Schneider and Wookcock 2008). Also, density has been found to provide the strongest information content in actual tests (Ewing *et al.* 2002). A powerful threshold used to define sprawl is when the rate of land development is greater than that of population growth (Davis and Schaub 2005). But while this can be an indication to detect hot spots for further inspection, it cannot be a general condition. This threshold tends to neglect development in order to accommodate non-residents, such as second-home owners and tourists, which in some areas cannot be considered excessive. Several flavours of density can be used including gross, net and residential where the denominator is the acreage of the zone, urban area or residential land, respectively. The numerator is typically the total number of resident population but can also be the number of households or some other socioeconomic variable.

As sprawl is a way of growth, it is a trend in time rather than a fixed state (Hess *et al.* 2001). For that reason a second dimension often selected to operationalise sprawl is its dynamics or change in time. Notions such as growth rate (Frenkel and Ashkenazi 2008) or intensification (Burton 2002) have been introduced. Notably, both these terms imply positive signs of change which in fact is not always the case today as some cities are actually shrinking. There is less consensus over the other dimensions used with each researcher apparently proposing a different set of *ad hoc* dimensions. In that respect only two more dimensions will be mentioned here, suitable for a cross-country comparison with a minimal set of data. One of them is urban composition which is used primarily to examine the mix of uses non-spatially, in terms of proportions. Percentages of residential and commercial land uses are primarily measured. The ratio of open space compared with the total urban area can also be an attribute. This quantity is termed porosity (Huang *et al.* 2007). The other dimension is urban configuration. It is used to describe the spatial form of the city. An attribute of this dimension can be the irregularity of the shape or the scattering and fragmentation of urban areas (Frenkel and Ashkenazi 2008). The segregation of land uses can also be an attribute.

Each dimension requires a different set of metrics (Frenkel and Ashkenazi 2008). The metrics adopted in the second step are always limited by data availability. Typically in national studies data are abundant, and therefore, metrics are more detailed. Examples of such studies include those for the United States (Wassmer 2000), the United Kingdom (Burton 2002) and Israel (Frenkel and Ashkenazi 2008). Cross-country studies are hampered by the lack of data. The European Union is hardly an exception to this rule. The few studies comparing cities in different European countries that exist are confined to a very high level of spatial abstraction (Kasanko *et al.* 2006, Schwarz 2010, Mubareka *et al.* 2011).

Recently spatial metrics adopted from landscape ecology have been used in urban environments (Herold *et al.* 2003, 2005). Spatial metrics can leverage the potential to understand and model urban dynamics (Herold *et al.* 2003). With these metrics, the composition and configuration of urban landscapes can be quantified and measured. However, the transfer of metrics from landscape ecology to urban planning is not always straightforward. One problem in particular is associated with the notion of patches, i.e. homogeneous regions used in landscape ecology. The problem is that urban patches, formed from different land uses, are artificially fragmented due to the street network, not due to real differences in characteristics. The street network that constantly interrupts land uses has variable width. Therefore, unless some prior transformation, such as resampling, is done, patch metrics can be misleading. For example, a typical measure in landscape ecology is patch density or the number of patches per unit area. If this is applied to describe residential land use in an urban area for example, the results could be more dependent on the street network structure and less to the mix of land uses.

Landscape ecology metrics have recently been applied to urban data at national level with interesting results (Prastacos *et al.* 2012). Overall, it can be said that the problem with landscape metrics is not to think of new ones but rather how to meaningfully apply them using the available urban data. It has been suggested that a key factor in selecting metrics is keeping data requirements modest and interpretation as intuitive as possible (Jaeger *et al.* 2010). Tsai (2005) has found that Moran's I coefficient, a measure of spatial autocorrelation, can be used as a single value to significantly describe urban configuration and distinguish sprawl from compact forms.

The third step has to do with checking for correlation amongst metrics (Huang *et al.* 2007, Schwarz 2010). Especially when a number of metrics are used per dimension, a test is performed to check whether they contain independent information or rather some of them are redundant (Mubareka *et al.* 2011). Dimensions themselves are also checked for correlation. This step is more meaningful for national surveys, given the plethora of variables that can be facilitated by the available data, to limit the number of metrics used. More sophisticated methods of feature selection or feature extraction could be used in analogy to reducing input features in classification tasks (Stathakis and Perakis 2007).

The fourth step has to do with finding a way to summarise knowledge learned from metrics. Two choices are evident in the literature, either merge them to yield a single sprawl metric or leave them independent and use some clustering technique to form groups of cities based on sprawl. A common strategy in the single sprawl metric approach is first to normalise each metric, then combine metrics per characteristic and then combine all characteristics to get a single number. Burton (2002) used averaging as a means for combining in order to obtain a single compactness indicator. The underlining assumption being that all metrics are of equal importance. For metrics or dimensions of different importance, different weights can be applied. However, it is often hard to justify the differentiation of weights. Frenkel and Ashkenazi (2008) used factor analysis to weigh several measures to produce one integrated sprawl index. Schwarz (2010) used cluster analysis, and Huang *et al.* (2007) used *k*-means clustering method to form groups of cities based on several metrics rather than a single sprawl index.

In this context, the objective of this article is to compare medium-sized European cities in terms of compactness. The novelty relies mainly on the fact that the analysis is done at higher spatial resolution than any cross-European comparison presented before. The metrics used are not limited only to land cover as in the previous cross-European studies. Land use information is also included to measure the mix of use in a spatial manner. In addition, some new spatial metrics are introduced to adapt to this increased spatial and thematic resolution which permits a cross-national comparison with a strong spatial dimension at the city level in Europe. By no means is it claimed that these are the only possible metrics or even the best metrics to be used. It is evident however in the results that some initial reasonable and comparable results can be drawn based on the proposed approach. The data sets used are described in Section 2. The method is presented in Section 3. Results are shown in Section 4, and conclusions are drawn in Section 5.

2. Data

A dilemma typically faced in any study comparing cities is how to deal with the fact that they greatly vary in size. One way to overcome this difficulty is to include size itself as a dimension of sprawl. Such metrics include the size of continuous or discontinuous urban area or the total area of the city (Schwarz 2010). It has been suggested, however, that metrics should have monotonous reaction to increases of urban area (Jaeger *et al.* 2010). Overall, it currently appears that the sensitivity of the metrics typically used to varying city sizes is not fully understood. In that respect, it is probably safer, in order to maintain comparability, to include in the data set only medium-sized cities. Medium-sized cities are also considered to be closer to the compact city arguments (Burton 2002). However, there is no commonly accepted definition of the medium-sized city (Rudolf *et al.* 2007). Different definitions have been introduced in the literature depending on the amount of urban population, the urban system characteristics, the working scale as well as other factors. A detailed literature review about this topic is beyond the scope of the present study. The definition adopted in the sequel is in line with the Urban Audit project. Therefore cities with population between 50,000 and 250,000 inhabitants are classified as medium sized (Eurostat 2004). The cities selected by this criterion are of second order at a European scale but of crucial importance at national and regional scales (Rudolf *et al.*

2007). Based on the specific data sets used, 74 cities were actually selected for comparison, having a large urban zone (LUZ) with total resident inhabitants between 82,539 (Suwalki) and 218,276 (Oradea). Burton (2002) applied a similar threshold.

As already stated, the two available data sets used are Urban Atlas and Urban Audit provided by the European Commission. The former is a land use data set suitable for a scale of 1/10.000. It does not cover exhaustively the territory of Europe. It only covers urban areas with over 100.000 inhabitants, the so-called LUZs. The date of the data set is 2005–2007. No archive versions are available. Originally, this data set is offered in vector format, but it was converted to a raster with 10-meter resolution for convenience in subsequent analysis. It is a product of interpretation of high-resolution earth observation data combined with locally available topographic and land use maps. Although Urban Atlas aligns hierarchically with the classification system of CORINE land cover data set, the construction of a time series combining the two is not straightforward due to significant scale differences (1/100.000 for CORINE and 1/10.000 for Urban Atlas). The land use classes provided for LUZs by Urban Atlas are shown on Table 1.

The land uses shown on Table 1 are grouped in the following classes for the purpose of this study.

- Built-up areas: codes 11100 up to 14200 (inclusive)
- Residential areas: codes 11100 up to 11300 (inclusive)
- Low-density areas: codes 11230 up to 11300 (inclusive)
- Open spaces: code 14100 and 14200
- Construction sites: code 13300
- Derelict land: code 13400
- Industrial/commercial/military: code 12100

Table 1. Land use classes in Urban Atlas.

Code	Land use
11100	Continuous urban fabric
11210	Discontinuous dense urban fabric
11220	Discontinuous medium-density urban fabric
11230	Discontinuous low-density urban fabric
11240	Discontinuous very low density urban fabric
11300	Isolated structures
12100	Industrial, commercial, public, military and private units
12210	Fast transit roads and associated land
12220	Other roads and associated land
12230	Railways and associated land
12300	Port areas
12400	Airports
13100	Mineral extraction and dump sites
13300	Construction sites
13400	Land without current use
14100	Green urban areas
14200	Sports and leisure facilities
20000	Agricultural areas, semi-natural areas and wetlands
30000	Forests
50000	Water

Obviously, this grouping is not free of generalisations. First, residential areas are not purely residential but merely predominantly residential (CEC 2011b). Second, the land use with code 12100 includes such diverse features as industrial, commercial and military at unknown proportions. Clearly, army camps have a very different functional linkage with the city and can occupy significant areas on the ground. Other minor generalisations can be observed.

Urban Audit on the other hand is a source of statistical information for the same LUZs, including population parameters. The most recent date for obtaining total resident population for all LUZs is 2004. This is with the exception of all LUZs in Bulgaria where the most recent date is 1991 and the exceptions of Lincoln (UK) and Setubal (PT) where the date is 2001. Several other variables exist in Urban Audit, but the data are incomplete. Consequently, these variables cannot be used with spatial metrics.

The reliability of the two sources is not clear. The nominal thematic accuracy of Urban Atlas for classes related to artificial surfaces is 85% or higher with a minimum mapping unit of 0.25 ha for artificial surfaces and 1 ha for all other classes. But in practice it is not easy to evaluate the actual thematic accuracy of Urban Atlas. It is still unclear whether even CORINE land cover program is within the nominal thematic accuracy given. Urban Audit errors are much easier to track. For example the total resident population for the LUZ containing Volos (gr006) is underestimated by almost 100% based on national statistics. At the same time, Kavala's (gr008) population is found to be larger than that of Volos, but again this is wrong based on national statistics. As a result Volos is not included in the following analysis, although it is by all means a typical medium-sized city.

Overall, it is assumed that inaccuracies and generalisation in these data sets are not strong enough to spoil the analysis. Preliminary experiments with compact city metrics are possible and meaningful. Nevertheless, it is perhaps surprising that these two data sources combined can in fact yield only 10% of the compactness metrics proposed by Burton (2002) in a national UK study. Another fundamental parameter is that Urban Atlas currently provides data for only one point in time. Obviously, this makes metrics related to the dynamics of change (growth rate, intensification, etc.) particularly difficult to be devised.

An option that was discarded was to use CORINE land cover as the source of the spatial data. The benefit would be the time series offered by CORINE which includes updates for 1990, 2000, 2006 and the soon to be released 2012. But a number of drawbacks cannot be neglected. CORINE, as already explained, offers land cover not land use classes. Hence any effort to measure the mix of use is impossible. Also, the scale is far too general to examine medium-sized cities. A medium-sized city is often contained in a 100 × 100 pixel box at CORINE's resolution. How much information can this contain?

3. Method

Based on the introductory discussion, four dimensions are selected to capture sprawl, namely density, dynamics, composition and configuration. The metrics selected for each dimension are not many due to data limitations. Correlation is then performed to understand the information content of each variable, but eventually no metric is discarded given that the set is already too small to be further reduced. The metrics have been standardised based on Equation (1) and combined together per dimension based on averaging. For example to obtain a single value for *density* all its metrics are averaged and so on. A single compactness value is then produced by averaging the values of each dimension.

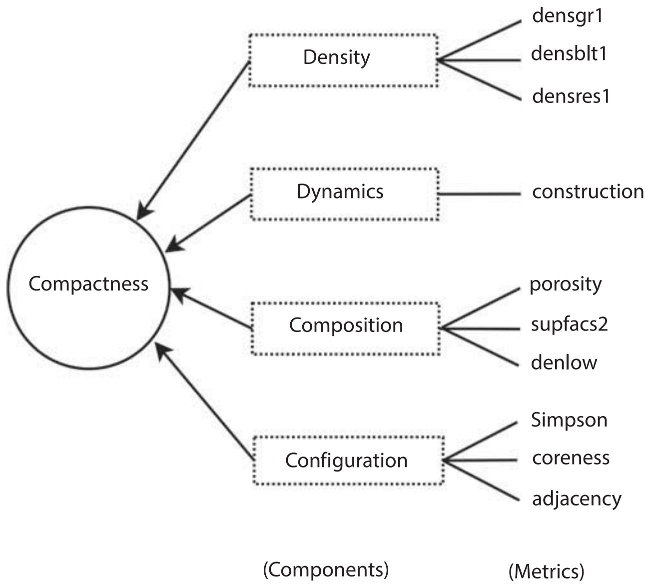

Figure 1. Metrics used to estimate the four dimensions of compactness and in turn compactness itself.

$$\text{Standardised value} = \frac{\text{value} - \text{mean}}{\text{standard deviation}} \tag{1}$$

The overall diagram of compactness with its dimensions and metrics is shown in Figure 1. The remaining part of this section is devoted to explaining the metrics used.

3.1. *Density*

Existing density metrics include *densgr1, densblt1* and *densres1.* The first one, *densgr1,* refers to the number of persons per hectare. It is gross density using the total area of the LUZ. Therefore, it is a biased metric since the delineation of a LUZ can be loose, directly affecting the result. Using administrative units to calculate spatial metrics limits the interpretability of results due to the Modifiable Aerial Unit Problem. It has been observed that the delineation of LUZs in Europe is not systematic (Mubareka *et al.* 2011). Take, for example, the population of the city of Ioannina (gr007) that is seven times smaller compared with that of Thessaloniki (gr002l). Their LUZs' acreage is surprisingly roughly the same. A less-biased metric is net density *densblt1* or the number of persons per hectare in built-up areas. Residential density *densres1*, which is the number of persons per hectare in residential built-up areas, is also efficient. This finding is in agreement with Kasanko *et al.* (2006), suggesting that net and residential density are less prone to artificial variations caused by administrative borders.

3.2. *Dynamics*

As time series data are not available, there is currently no direct way to calculate the trend of compactness. One of the few possibilities to implement a proxy variable is by *construction.* This is the ratio of construction site areas (code 13300) per total built-up areas. In other words, the amount of newly developed land is taken as a measure of intensification. The decision to include this metric is based on the fact that while its weakness is that it tends to confuse all growth for compactness, it is not the only one to do so. Other frequently used metrics, such as gross density *(densgr1*), have the same problem.

3.3. *Composition*

The first metric assessing the mixture of land uses is *supfacs2.* This is the ratio of residential (codes 11100–11300) to non-residential built-up land. It is a good indicator of mix. It is only an indication however and not a proof of mix since it has no spatial dimension. A second metric is porosity, that is, open spaces or the sum of land without current use (code 13400), green urban areas (code 14100) and sports and leisure facilities (code 14200) divided by built-up area. It is a measure of the amount of open spaces in the city. The third metric, *lowden,* refers to the ratio of low-density residential areas (codes 11230–11300) per total built-up area.

3.4. *Configuration*

While *composition* is a non-spatial metric of mix use, *configuration* is a spatial one to examine spatial patterns of mix. The first metric to describe configuration is *Simpson's index* (Simpson 1949). This is a metric frequently used in landscape ecology. It was used to estimate the probability of a built-up pixel being adjacent to an unbuilt pixel. This is a way to describe the degree of clustering of built-up areas. The second metric is a new quantity termed *coreness.* Suppose that the two cities in Figure 2 have the same density. Let us define the core area as the part inside the edge of the city based on a buffer distance. Consequently, the core is less close to the urban fringe and its characteristics less affected by it. Clearly, the core of the city is related to its shape. In this context, *coreness* is defined as the ratio of core built-up area to the total built-up area. To find the core built-up area, an internal buffer distance of 20 meters has been used. The exact distance is not that important since the point here is to make comparisons amongst cities using the same value.

Third, a newly introduced metric to take the spatial arrangement into consideration is *adjacency.* It is calculated by a 3 × 3 pixel moving window in a rasterised version of the data, with 10 × 10 m pixel. The concept is shown in Figure 3. Only two land uses are used

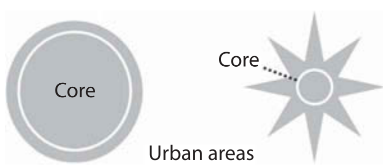

Figure 2. The concept of *coreness*.

R		R
C	R	
		C

	2	

Figure 3. Example of calculating *adjacency.* There are two different values (R = residential and C = commercial/industrial/military) in the left 3 × 3 window. The result (Equation (2)) is written in the central pixel of the output raster in the right.

in this raster, i.e. industrial/commercial/military and residential. Empty pixels are assigned to all other land uses and are ignored from the calculation. The number of different values within the 3 × 3 window is recorded and then averaged to yield the value of *adjacency*. The physical meaning of *adjacency* is related to measuring the spatial mixture of the two land uses. A larger size of window (5 × 5) has been tested to investigate the sensitivity of *adjacency*, but the results were essentially identical. The correlation coefficient of the 3 × 3 and 5 × 5 results is $R = 0.99$. The 5 × 5 window has been tested particularly in view of the effect of the street network given that urban land uses are fragmented by streets. It appears that 3 × 3 is enough to capture the variation, and its calculation is computationally faster. Note that while Simpson's index is used here as a metric of urban vs. non-urban mix, adjacency is used as a metric of land use mix. The two encapsulate different information content, and their correlation is low as shown in the sequel.

Other spatial metrics of configuration were also tested but not adopted in the end. One of them was based on the spatial difference (the Euclidean distance) between the gravity centres of residential and non-residential land use classes. It was discarded because it was found to ignore local spatial arrangements. For the same reason another tested metric based on the ratio of dispersion between the same two land use classes was discarded. In specific it was a ratio of the average nearest neighbour distance of the two classes.

4. Results

The outcome of the application of the metrics in absolute terms is shown in Table 2. The normalised and final results are shown in Table 3. The correlation of the values of Table 3 is shown in Tables 4 and 5. Based on Table 4, the only redundant variable could be either net (*densblt1*) or residential (*densres1*) density, which is very highly correlated ($R = 0.91$). Based on Table 5, it appears that density and configuration are the most important factors determining compactness.

Based on the rank in the last column of Table 3, it is evident that there is some geographic clustering of compactness. The trends are more visible on the map of Figure 4. Two trends are dominant. The first one is that some Eastern European countries have greater compactness values. This is probably due to the traditionally different planning system in these countries. This finding is in alignment with CEC (2006b) claiming that cities in former communist member states are characterised by more compact form reflecting both the strongly centralised planning systems and the heavy dependency on public transportation.

The second one is that cities in coastal areas and islands are substantially more compact. This finding is in agreement with Schneider and Woodcock (2008) who highlight that land availability is influenced by geophysical parameters such as mountains and the sea. In coastal areas and islands, land availability is typically restricted. Consequently, urban areas are de facto constrained by rigid natural borders, such as the sea and rough terrain. Kasanko *et al.* (2006) also agree that development options are very different in coastal areas compared with plain areas.

However, contrary to the findings of Kasanko *et al.* (2006), there is no north–south trend visible on the map in Figure 4, when focusing on Europe's mainland, excluding coastal areas and islands. The cities in the south do not appear to be more compact compared with the cities in the north or vice versa.

The last column of Table 3 is the rank of cities when gross density and construction are not taken into account. These two metrics are the weakest in the analysis. When they are removed the rank changes, but the overall pattern is not very different in most cases.

Table 2. Results of metrics as calculated.

City name	Code	Population	Zone area (ha)	Built-up (ha)	Residential (ha)	Open spaces (ha)	Low density (ha)	Construction sites (ha)	Built-up core (ha)	Adjacency (m)	Simpson (built-up)
		1	2	3	4	5	6	7	8	9	10
Brugge	be06	165,743	41,228	10,260	4953	709	1393	54	5907	0.0397	0.15
Namur	be07	139,024	39,741	9424	5640	721	3947	47	7484	0.0320	0.36
Pleven	bg05	206,936	179,197	11,400	5236	1415	503	13	9599	0.0200	0.12
Ruse	bg06	201,410	89,261	7374	2664	1270	113	67	5907	0.0238	0.15
Vidin	bg07	85,974	51,750	4462	2181	275	92	22	3489	0.0193	0.16
Ceske Budejovice	cz08	179,369	162,455	13,847	6440	1187	871	102	10,162	0.0265	0.16
Hradec Kralove	cz09	159,293	87,600	10,146	5030	866	238	119	7839	0.0291	0.20
Pardubice	cz10	159,981	89,091	11,266	5187	1104	376	218	8918	0.0268	0.22
Zlin	Cz11	193,068	103,207	10,153	5755	739	902	41	7568	0.0236	0.18
Karlovy Vary	cz13	121,430	162,137	11,246	4109	2311	863	51	8076	0.0311	0.13
Jihlava	cz14	108,292	117,869	7668	3518	640	462	88	5305	0.0273	0.12
Weimar	de30	153,353	88,949	9241	3669	1258	282	25	6868	0.0319	0.19
Tartu	ee02	148,872	300,056	15,269	7858	598	3921	324	9003	0.0146	0.10
Santiago de Compostela	es11	186,332	135,165	17,203	9168	550	6999	818	10,297	0.0227	0.22
Toledo	es16	167,036	361,635	15,387	4411	576	1926	841	8543	0.0201	0.08
Logroño	es18	171,599	143,702	9401	2232	653	1252	383	6110	0.0222	0.12
Oulu	fi04	196,096	376,836	21,387	10,179	2698	9420	188	15,168	0.0122	0.11
Poitiers	fr21	216,847	176,075	21,018	10,144	1819	2035	228	15,108	0.0404	0.21
Ajaccio	fr27	83,026	101,502	6502	3740	285	1025	89	4391	0.0165	0.12
Iraklio	gr04	202,426	60,447	6179	3399	210	982	102	4628	0.0251	0.18
Larissa	gr05	187,831	155,570	11,651	4023	364	637	106	7281	0.0151	0.14
Ioannina	gr07	139,522	132,632	9364	3575	291	725	305	5804	0.0255	0.13
Kavala	gr08	129,567	35,148	2505	1101	104	204	21	1878	0.0173	0.13
Nyíregyháza	hu03	218,153	143,765	17,861	12,109	457	988	345	15,004	0.0189	0.22
Pécs	hu04	178,190	57,066	8857	5242	454	748	20	7403	0.0192	0.26
Szeged	hu06	197,417	75,292	10,799	6154	999	1185	24	8717	0.0314	0.25

(*continued*)

Table 2. (*Continued*).

City name	Code	Population	Zone area (ha)	Built-up (ha)	Residential (ha)	Open spaces (ha)	Low density (ha)	Construction sites (ha)	Built-up core (ha)	Adjacency (m)	Simpson (built-up)
Kecskemét	hu08	170,452	148,304	16,229	9348	743	2482	193	11,687	0.0242	0.19
Székesfehérvár	hu09	155,877	114,417	11,685	6031	1080	109	324	9773	0.0236	0.18
Cremona	it13	132,159	66,133	8132	2892	460	668	119	5908	0.0302	0.22
Trento	it14	185,452	77,916	8168	3614	299	1350	69	5393	0.0268	0.19
Perugia	it16	207,569	80,602	11,612	5433	669	3072	88	7383	0.0215	0.25
Ancona	it17	208,235	40,844	8351	3729	478	1970	243	5827	0.0251	0.33
l'Aquila	it18	100,592	158,778	8637	4165	271	1379	64	5149	0.0162	0.10
Campobasso	it20	116,507	130,868	9613	5049	199	3004	139	4849	0.0135	0.14
Potenza	it23	145,337	149,847	11,470	4948	163	3381	102	5458	0.0177	0.14
Catanzaro	it24	146,730	76,141	6356	3008	174	1858	82	3433	0.0156	0.15
Sassari	it26	200,554	122,648	12,326	5903	510	3698	244	8382	0.0197	0.18
Foggia	it31	196,072	104,812	7128	2012	271	963	99	4133	0.0202	0.13
Panevezys	lt03	160,656	222,822	12,981	5972	815	1765	292	8652	0.0167	0.11
Liepaja	lv02	131,788	365,731	11,136	4529	1016	2277	98	6325	0.0116	0.06
Valletta	mt01	208,542	24,671	8815	3900	421	612	25	7135	0.0237	0.46
Apeldoorn	nl14	212,948	62,505	11,832	5551	1726	2170	59	8981	0.0335	0.31
Leeuwarden	nl15	158,883	45,205	7870	3313	981	825	90	6187	0.0354	0.29
Gorzów Wielkopolski	pl17	190,251	130,538	9552	4531	1111	757	196	6633	0.0252	0.14
Zielona Góra	pl18	207,451	162,701	11,222	4862	1224	210	235	8366	0.0308	0.13
Jelenia Góra	pl19	127,382	58,565	6267	3587	578	668	16	4684	0.0344	0.19
Nowy Sacz	pl20	158,620	44,835	7636	5467	245	1210	17	5033	0.0240	0.28
Suwalki	pl21	82,539	61,833	4211	2227	219	1011	9	2475	0.0143	0.13
Konin	pl22	143,305	75,844	8337	4097	462	1087	88	5527	0.0204	0.20
Koszalin	pl28	171,469	175,106	9248	3983	1036	867	71	6244	0.0223	0.10
Funchal	pt04	190,014	26,095	6234	4037	458	764	98	4633	0.0262	0.36
Setubal	pt06	113,811	17,283	4253	1927	262	397	65	3297	0.0241	0.37
Ponto Delgada	pt07	119,571	53,714	5859	2780	257	925	60	3765	0.0330	0.19
Aveiro	pt08	112,873	27,335	6351	3391	398	291	245	4932	0.0260	0.36

(*continued*)

Table 2. (*Continued*).

City name	Code	Population	Zone area (ha)	Built-up (ha)	Residential (ha)	Open spaces (ha)	Low density (ha)	Construction sites (ha)	Built-up core (ha)	Adjacency (m)	Simpson (built-up)
Faro	pt09	111,782	48,217	5415	2760	204	1488	42	3252	0.0173	0.20
Oradea	ro06	218,276	20,110	5307	2425	213	74	107	4456	0.0254	0.39
Bacau	ro07	203,559	22,078	4235	2246	221	54	17	3514	0.0357	0.31
Arad	ro08	189,099	51,978	6623	3350	262	90	18	5595	0.0326	0.22
Sibiu	ro09	186,803	58,814	4694	2152	230	143	278	3888	0.0409	0.15
Targu Mures	ro10	172,642	14,135	3224	1763	162	44	2	2716	0.0515	0.35
Piatra Neamt	ro11	124,194	14,671	2561	1452	61	43	5	2164	0.0319	0.29
Calarasi	ro12	83,441	24,578	2149	762	66	40	15	1802	0.0275	0.16
Alba Iulia	ro14	97,745	25,882	3053	1643	132	102	7	2423	0.0415	0.21
Jönköping	se04	148,693	347,332	18,894	8138	2122	7738	245	11,772	0.0181	0.10
Umeå	se05	139,588	981,210	25,950	12,494	1383	10,988	441	14,151	0.0136	0.05
Linköping	se07	183,221	423,193	23,690	9989	2772	8643	70	14,397	0.0286	0.11
Örebro	se08	178,748	368,777	22,975	11,409	2158	10,694	141	14,938	0.0190	0.12
Banska Bystrica	sk03	111,419	80,887	4907	2079	478	136	39	3450	0.0256	0.11
Nitra	sk04	163,764	87,020	9516	5261	797	146	51	7748	0.0291	0.19
Presov	sk05	163,743	93,455	8012	4355	523	160	159	6100	0.0250	0.16
Žilina	sk06	156,869	81,391	7814	3870	502	259	349	6072	0.0239	0.17
Trnava	sk07	126,822	74,092	7678	3412	603	181	276	6128	0.0322	0.19
Trencín	sk08	112,515	67,404	6002	2877	342	296	26	4304	0.0295	0.16
Lincoln	uk19	164,418	72,378	10,076	4528	1180	1226	83	8290	0.0241	0.24

Table 3. Normalised results of metrics and combination into components of compactness.

Code	Densgr1	Densblt1	Densres1	Construction	Lowden	Porosity	Supfacs2	Adjacency	Simpson built-up	Coreness	Density	Dynamics	Composition	Configuration	Compactness	Rank	(Rank*)
	11 = 1/2	12 = 1/3	13 = 1/4	14 = 7/3	15 = 6/3	16 = 5/3	17 = 4/(3–4)	18 = 9	19 = 10	20 = 8/3	[11 to 13]	14	[15 to 17]	[18 to 20]			
be06	0.61	−0.38	−0.42	−0.67	0.01	0.91	−0.10	1.88	−0.47	−1.43	−0.07	−0.67	0.49	−0.01	−0.07	34	(31)
be07	0.39	−0.51	−0.80	−0.69	2.31	−0.19	1.47	0.88	2.01	0.85	−0.33	−0.69	2.13	1.53	0.66	8	(6)
bg05	−0.57	−0.18	−0.16	−0.99	−0.74	1.22	−0.34	−0.66	−0.85	1.35	−0.33	−0.99	0.08	−0.07	−0.33	54	(33)
bg06	−0.12	0.70	1.41	−0.37	−0.97	0.81	−1.14	−0.17	−0.47	0.92	0.72	−0.37	−0.77	0.12	−0.08	37	(27)
bg07	−0.36	−0.08	−0.16	−0.68	−0.93	−0.02	−0.04	−0.76	−0.40	0.72	−0.22	−0.68	−0.59	−0.18	−0.42	59	(48)
cz08	−0.59	−0.69	−0.66	−0.50	−0.59	−1.26	−0.28	0.17	−0.41	0.22	−0.70	−0.50	−1.26	−0.01	−0.62	70	(67)
cz09	−0.30	−0.42	−0.50	−0.16	−0.91	−0.61	0.04	0.51	0.16	0.63	−0.44	−0.16	−0.88	0.53	−0.24	46	(46)
cz10	−0.31	−0.57	−0.53	0.43	−0.83	−0.94	−0.33	0.21	0.35	0.82	−0.51	0.43	−1.24	0.57	−0.19	44	(52)
cz11	−0.28	−0.10	−0.42	−0.76	−0.37	−0.64	0.96	−0.20	−0.16	0.34	−0.29	−0.76	−0.03	−0.01	−0.27	49	(37)
cz13	−0.74	−0.90	−0.59	−0.72	−0.47	−0.91	−1.11	0.77	−0.73	0.06	−0.81	−0.72	−1.47	0.04	−0.74	74	(70)
cz14	−0.67	−0.58	−0.54	−0.18	−0.61	−1.10	−0.34	0.28	−0.82	−0.22	−0.65	−0.18	−1.21	−0.31	−0.59	67	(68)
de30	−0.34	−0.34	−0.06	−0.87	−0.85	0.17	−0.88	0.88	−0.06	0.32	−0.27	−0.87	−0.92	0.47	−0.40	57	(42)
ee02	−0.85	−1.00	−1.05	0.58	0.99	−0.86	0.26	−1.36	−1.11	−1.29	−1.05	0.58	0.23	−1.54	−0.45	61	(71)
es11	−0.48	−0.90	−0.99	2.64	2.22	−0.67	0.49	−0.31	0.36	−1.20	−0.86	2.64	1.21	−0.47	0.63	9	(34)
es16	−0.86	−0.89	−0.23	3.20	−0.08	0.35	−1.61	−0.65	−1.29	−1.65	−0.72	3.20	−0.79	−1.47	0.05	27	(74)
es18	−0.56	−0.17	1.46	2.11	−0.01	−0.92	−1.86	−0.38	−0.81	−0.66	0.26	2.11	−1.65	−0.76	−0.01	32	(60)
fi04	−0.84	−1.06	−1.03	−0.39	2.49	−0.93	−0.17	−1.68	−0.99	−0.04	−1.06	−0.39	0.82	−1.11	−0.43	60	(58)
fr21	−0.54	−0.95	−0.94	−0.23	−0.31	0.91	−0.10	1.98	0.22	0.06	−0.88	−0.23	0.30	0.93	0.03	28	(28)
fr27	−0.71	−0.71	−0.91	−0.01	0.19	−0.36	1.09	−1.12	−0.84	−0.39	−0.84	−0.01	0.54	−0.96	−0.32	53	(54)
gr04	0.33	1.23	0.71	0.21	0.20	0.78	0.72	0.00	−0.09	0.38	0.82	0.21	1.01	0.12	0.54	12	(11)
gr05	−0.55	−0.38	0.15	−0.36	−0.65	1.45	−1.25	−1.30	−0.62	−0.92	−0.28	−0.36	−0.27	−1.16	−0.52	65	(59)
gr07	−0.62	−0.50	−0.18	1.47	−0.47	0.02	−1.00	0.04	−0.71	−0.97	−0.47	1.47	−0.86	−0.67	−0.13	42	(64)
gr08	0.47	3.07	3.23	−0.43	−0.44	−0.01	−0.52	−1.01	−0.69	0.39	2.45	−0.43	−0.57	−0.54	0.23	18	(12)
hu03	−0.42	−0.76	−1.09	0.43	−0.65	−0.70	3.21	−0.80	0.31	1.33	−0.82	0.43	1.10	0.34	0.26	17	(25)
hu04	0.24	0.01	−0.40	−0.90	−0.41	0.64	1.36	−0.78	0.83	1.29	−0.05	−0.90	0.94	0.55	0.13	23	(17)
hu06	0.03	−0.17	−0.48	−0.90	−0.20	2.88	1.01	0.80	0.64	0.99	−0.22	−0.90	2.18	1.00	0.51	14	(7)
hu08	−0.58	−0.93	−1.08	−0.15	0.15	0.04	1.10	−0.12	0.04	0.08	−0.94	−0.15	0.76	0.00	−0.08	39	(35)
hu09	−0.49	−0.65	−0.75	1.09	−1.02	0.49	0.28	−0.20	−0.09	1.29	−0.68	1.09	−0.15	0.41	0.17	22	(40)
it13	−0.22	−0.37	0.11	0.07	−0.43	−1.01	−1.18	0.65	0.29	0.14	−0.17	0.07	−1.55	0.44	−0.30	52	(53)
it14	−0.07	0.26	0.35	−0.42	0.25	−0.47	−0.50	0.21	−0.04	−0.55	0.20	−0.42	−0.43	−0.16	−0.20	45	(36)
it16	0.01	−0.21	−0.21	−0.48	1.06	0.17	−0.25	−0.47	0.65	−0.81	−0.15	−0.48	0.58	−0.26	−0.08	38	(30)

(*continued*)

Table 3. (*Continued*).

Code	Densgr1	Densblt1	Densres1	Construction	Lowden	Porosity	Supfacs2	Adjacency	Simpson built-up	Coreness	Density	Dynamics	Composition	Configuration	Compactness	Rank	(Rank*)
it17	1.05	0.47	0.55	1.20	0.82	−0.47	−0.46	−0.01	1.58	−0.16	0.75	1.20	−0.06	0.58	0.62	10	(18)
it18	−0.79	−0.82	−0.82	−0.50	0.20	0.45	−0.11	−1.15	−1.04	−1.22	−0.88	−0.50	0.32	−1.40	−0.61	69	(65)
it20	−0.68	−0.77	−0.87	0.05	1.45	−0.67	0.39	−1.50	−0.65	−2.18	−0.84	0.05	0.69	−1.78	−0.47	63	(66)
it23	−0.65	−0.72	−0.60	−0.38	1.30	−0.80	−0.60	−0.97	−0.59	−2.48	−0.71	−0.38	−0.06	−1.66	−0.70	73	(72)
it24	−0.25	0.29	0.24	−0.07	1.28	−0.44	−0.20	−1.24	−0.45	−1.81	0.10	−0.07	0.38	−1.44	−0.26	48	(45)
it26	−0.37	−0.37	−0.40	0.47	1.35	−0.48	−0.14	−0.71	−0.12	−0.34	−0.41	0.47	0.43	−0.48	0.00	30	(39)
it31	−0.28	0.72	2.35	0.01	0.00	1.10	−1.63	−0.64	−0.76	−1.39	1.01	0.01	−0.31	−1.14	−0.11	41	(29)
lt03	−0.75	−0.75	−0.70	0.68	0.01	−0.30	−0.33	−1.10	−0.96	−0.48	−0.80	0.68	−0.37	−1.04	−0.38	56	(69)
lv02	−0.90	−0.80	−0.61	−0.39	0.57	3.74	−0.80	−1.76	−1.55	−1.52	−0.84	−0.39	2.08	−1.98	−0.28	50	(41)
mt01	2.44	0.35	0.45	−0.86	−0.53	1.37	−0.50	−0.19	3.15	1.01	1.17	−0.86	0.20	1.63	0.54	13	(9)
nl14	0.36	−0.20	−0.21	−0.69	0.40	−0.20	−0.24	1.08	1.36	0.48	−0.02	−0.69	−0.02	1.20	0.12	24	(19)
nl15	0.40	0.01	0.21	−0.18	−0.24	0.05	−0.69	1.33	1.13	0.77	0.22	−0.18	−0.52	1.33	0.21	20	(20)
pl17	−0.45	−0.01	−0.05	0.52	−0.45	−0.34	−0.19	0.00	−0.65	−0.19	−0.18	0.52	−0.58	−0.34	−0.15	43	(49)
pl18	−0.52	−0.15	−0.02	0.56	−0.95	−0.83	−0.58	0.73	−0.74	0.34	−0.25	0.56	−1.40	0.14	−0.24	47	(57)
pl19	−0.15	0.03	−0.33	−0.87	−0.23	−0.65	1.05	1.19	0.00	0.36	−0.16	−0.87	0.10	0.64	−0.07	36	(24)
pl20	0.41	0.07	−0.61	−0.90	0.19	−0.08	4.39	−0.14	1.07	−0.56	−0.05	−0.90	2.66	0.15	0.47	15	(8)
pl21	−0.50	−0.04	−0.26	−0.91	0.86	−0.77	0.43	−1.40	−0.76	−1.31	−0.29	−0.91	0.31	−1.42	−0.58	66	(55)
pl22	−0.27	−0.28	−0.35	−0.25	−0.04	−0.70	−0.01	−0.61	0.05	−0.52	−0.33	−0.25	−0.44	−0.44	−0.37	55	(51)
pl28	−0.65	−0.15	0.00	−0.47	−0.34	−0.73	−0.60	−0.37	−1.07	−0.39	−0.29	−0.47	−0.99	−0.75	−0.62	71	(62)
pt04	1.96	1.01	0.17	0.15	−0.10	2.79	2.46	0.14	2.03	0.32	1.14	0.15	3.05	1.02	1.34	1	(2)
pt06	1.67	0.65	0.69	0.12	−0.34	0.87	−0.40	−0.13	2.11	0.65	1.09	0.12	0.08	1.08	0.59	11	(14)
pt07	−0.13	0.03	−0.01	−0.28	0.19	0.51	−0.19	1.01	0.04	−0.74	−0.04	−0.28	0.30	0.13	0.03	29	(26)
pt08	0.65	−0.22	−0.43	1.93	−0.73	1.43	0.50	0.11	1.95	0.67	0.00	1.93	0.71	1.12	0.94	6	(15)
pt09	−0.09	0.06	−0.11	−0.47	1.14	1.63	0.20	−1.01	0.10	−1.17	−0.05	−0.47	1.76	−0.85	0.10	25	(21)
ro06	3.43	2.04	2.03	0.50	−0.99	0.72	−0.36	0.03	2.32	1.33	2.72	0.50	−0.37	1.51	1.09	4	(5)
ro07	2.76	2.72	2.06	−0.76	−0.99	1.53	0.45	1.36	1.40	1.22	2.73	−0.76	0.59	1.63	1.05	5	(3)
ro08	0.45	0.82	0.58	−0.87	−0.99	−0.78	0.15	0.96	0.37	1.38	0.67	−0.87	−0.96	1.11	−0.01	33	(22)
ro09	0.26	1.92	1.89	3.55	−0.85	−0.35	−0.35	2.04	−0.52	1.21	1.47	3.55	−0.92	1.12	1.31	2	(10)
ro10	3.99	3.25	2.37	−1.03	−0.99	−0.89	0.67	3.40	1.89	1.36	3.48	−1.03	−0.72	2.73	1.12	3	(1)
ro11	2.44	2.76	1.84	−0.93	−0.96	−0.03	0.96	0.87	1.14	1.38	2.55	−0.93	−0.02	1.39	0.75	7	(4)
ro12	0.35	1.82	2.88	−0.54	−0.95	−0.52	−1.19	0.31	−0.37	1.32	1.83	−0.54	−1.57	0.52	0.06	26	(16)
ro14	0.51	1.16	0.71	−0.89	−0.83	−0.40	0.55	2.11	0.20	0.84	0.86	−0.89	−0.40	1.29	0.22	19	(13)

(*continued*)

Table 3. (*Continued*).

Code	Densgr1	Densblt1	Densres1	Construction	Lowden	Porosity	Supfacs2	Adjacency	Simpson built-up	Coreness	Density	Dynamics	Composition	Configuration	Compactness	Rank	(Rank*)
se04	−0.87	−1.18	−1.08	−0.06	2.24	−0.70	−0.60	−0.92	−1.04	−0.94	−1.13	−0.06	0.56	−1.19	−0.46	62	(61)
se05	−0.99	−1.42	−1.39	0.25	2.35	−0.93	−0.11	−1.50	−1.64	−1.75	−1.38	0.25	0.78	−2.01	−0.59	68	(73)
se07	−0.87	−1.20	−1.07	−0.85	1.87	−1.16	−0.68	0.44	−1.01	−1.10	−1.14	−0.85	0.02	−0.68	−0.66	72	(63)
se08	−0.85	−1.19	−1.19	−0.60	2.69	−1.33	0.05	−0.80	−0.87	−0.66	−1.17	−0.60	0.83	−0.96	−0.47	64	(56)
sk03	−0.48	0.26	0.45	−0.45	−0.87	0.11	−0.66	0.06	−0.91	−0.10	0.08	−0.45	−0.84	−0.39	−0.40	58	(47)
sk04	−0.27	−0.28	−0.52	−0.66	−0.97	0.83	0.76	0.52	0.04	1.06	−0.39	−0.66	0.37	0.66	0.00	31	(23)
sk05	−0.33	0.04	−0.24	0.47	−0.94	−0.70	0.63	−0.02	−0.41	0.51	−0.19	0.47	−0.60	0.03	−0.07	35	(43)
sk06	−0.25	0.00	−0.11	2.41	−0.83	−0.47	0.03	−0.16	−0.21	0.67	−0.13	2.41	−0.75	0.12	0.41	16	(44)
sk07	−0.34	−0.34	−0.26	1.74	−0.91	−1.02	−0.48	0.91	−0.06	0.89	−0.34	1.74	−1.43	0.71	0.17	21	(50)
sk08	−0.36	−0.13	−0.17	−0.74	−0.70	0.31	−0.14	0.56	−0.34	0.04	−0.24	−0.74	−0.31	0.11	−0.30	51	(38)
uk19	−0.11	−0.36	−0.30	−0.44	−0.11	0.04	−0.43	−0.14	0.57	1.15	−0.28	−0.44	−0.30	0.65	−0.09	40	(32)

Note: Rank* is the rank if *densgr1* and construction are not taken into account.

Table 4. Correlation between metrics used.

	Densgrl	Densbltl	Densresl	Construction	Lowden	Porosity	Supfacs2	Adjacency	Simpson	Coreness
Densgrl	–	0.79	0.62	−0.15	−0.32	0.27	0.22	0.48	0.81	0.49
Densbltl	–	–	0.91	−0.10	−0.46	0.18	0.06	0.42	0.43	0.48
Densresl	–	–	–	0.01	−0.45	0.15	−0.26	0.32	0.26	0.36
Construction	–	–	–	–	−0.02	−0.12	−0.20	−0.07	−0.11	−0.10
Lowden	–	–	–	–	–	−0.20	0.04	−0.45	−0.21	−0.63
Porosity	–	–	–	–	–	–	0.08	−0.04	0.28	0.09
Supfacs2	–	–	–	–	–	–	–	0.06	0.36	0.23
Adjacency	–	–	–	–	–	–	–	–	0.42	0.51
Simpson	–	–	–	–	–	–	–	–	–	0.53
Coreness	–	–	–	–	–	–	–	–	–	–

Table 5. Correlation between dimensions used.

	Density	Dynamics	Composition	Configuration	Compactness
Density	–	−0.18	0.11	0.49	0.63
Dynamics	–	–	−0.20	−0.12	0.30
Composition	–	–	–	−0.08	0.30
Configuration	–	–	–	–	0.71
Compactness	–	–	–	–	–

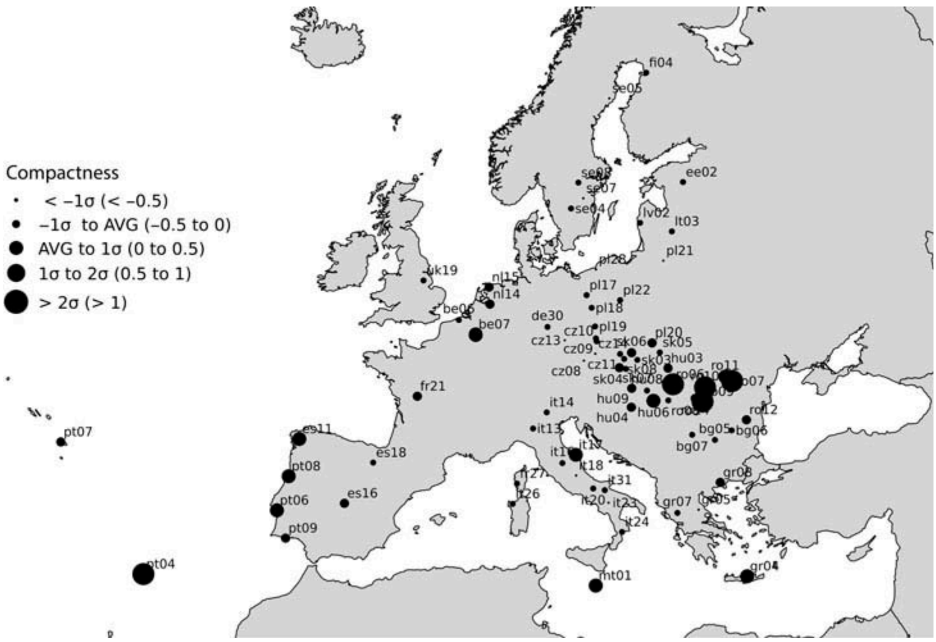

Figure 4. Compactness across European cities.

Some examples of metrics for cities are shown in Figure 5. The three columns of the table refer to examples of low, medium and high values, respectively. The first row is related to composition. The metric (*supfacs2*) captures the different proportions of residential to non-residential land uses present. It is evident however that *adjacency* in the second row is a much better indicator of the actual spatial mix of these two land use types. Spatial mix is more difficult, but perhaps more important in the description of urban form.

In the third row of Figure 5, the dimension corresponding to dynamics is shown. It is evident there that as expected, the metric *construction* is only loosely related to compactness. The construction sites recorded are mainly in the urban periphery in the form of new highways and new infrastructure such as airports. Unfortunately, no distinction between urban and exurban constructions can be made based on the available data sets. In that respect, a high value in this metric could mean that the city is not intensified by more development within its core, but rather that it expands towards new infrastructures and

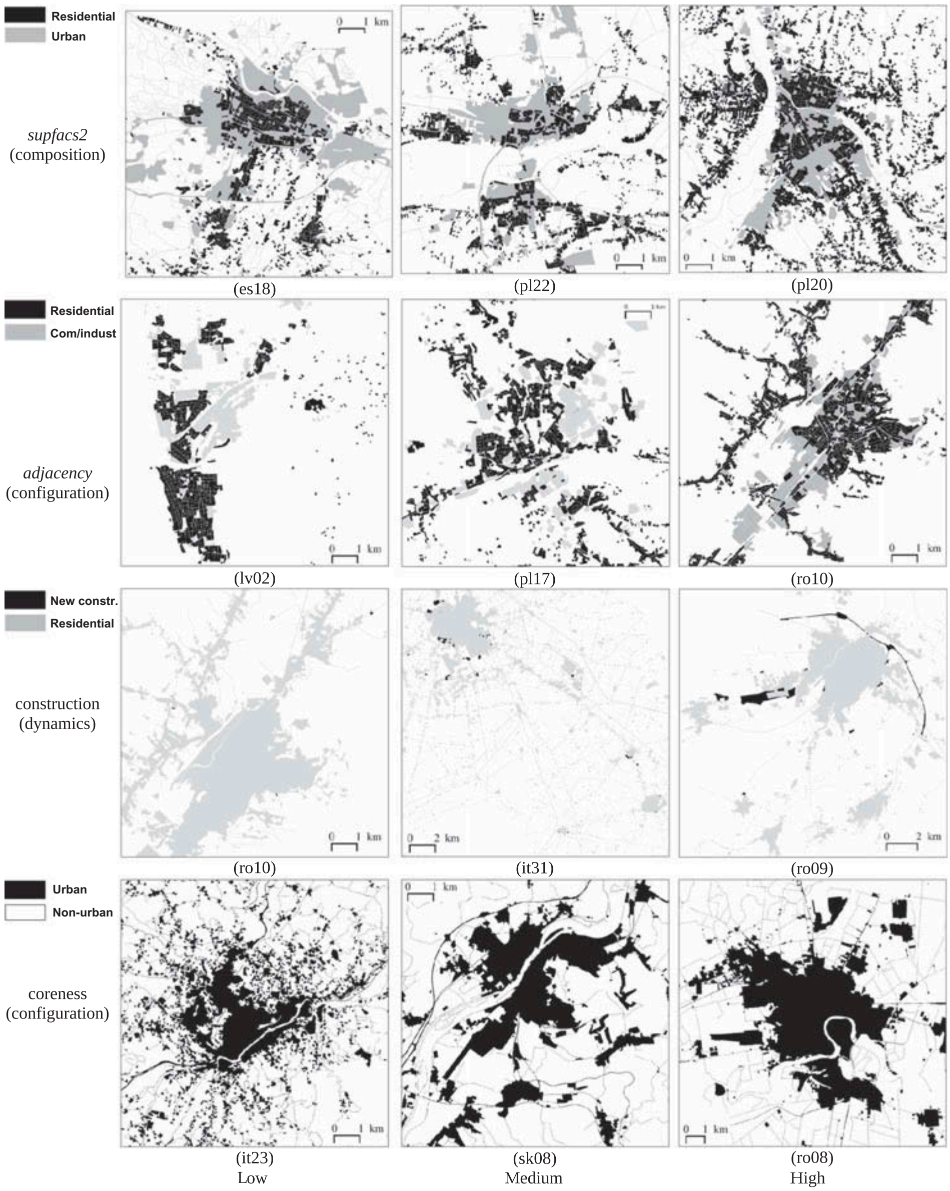

Figure 5. Examples of metrics and dimensions. Urban Atlas code in parenthesis.

along new highways. Low levels of *construction* are clearly however related to no intensification in any case.

The last row of Figure 5 refers to configuration. It is quite clearly displayed that *coreness* alone is a good measure of dispersion of the city or sprawl. This is a good and simple metric to capture land take dynamics and highlight inefficiently land consuming patterns due to sprawl.

5. Conclusions

The main finding has been that the compactness of medium-sized European cities can be quantified by urban metrics and compared cross-nationally despite the very limited availability of data. Although much more efficient metrics can be and are actually used in country specific studies, the low availability of European-wide data sets with common standards currently limits analysis to a minimal set of generic indexes. Surprisingly, given the plethora of existing data sets regarding other domains (environment, etc.), cities are relatively neglected despite their profound importance. In a way it appears that the focus has been on the end result (environmental problems, etc.) and not where it should be, i.e. to what drives the problems. More urban data with common standards are definitely needed. But, at the same time, custom metrics should be tailored adapted to available data sets in order to get the maximum information possible. Ignoring data availability and introducing data-aggressive metrics are not going to solve the problem. Also merely transferring concepts from other domains such as landscape ecology is not enough. This is an open field for future research. The metrics proposed here are limited in several aspects. In specific, density metrics are primarily prone to fluctuations due to differences in the way that administrative boundaries are delineated. The metrics used to capture dynamics are particularly weak as they have to be computed with data covering a single instance in time. Composition and configuration metrics are limited by the inevitable over-generalisation of land use classes due to the way that the original data were aggregated (e.g. having industrial in the same class with military and commercial).

Even though not all agree that sprawl is a problem, everybody should agree that at least it must be monitored. In that respect, the metrics are of high practical significance. On the one hand, they are a great toolkit for urban planners to understand how cities evolved to reach their current states. In this context, metrics are also useful to urban planners as an aid in defining sprawl itself. On the other hand, metrics are the only tangible means in order to set and monitor policy objectives towards compactness, provided that suitable data sets exist. In fact, metrics could be embedded in policies to constrain or guide growth towards specific metric signatures (Herold *et al.* 2003). At the European level, metrics should not be seen as a means to limit the diversity of cities, but rather to preserve this diversity by curtailing the homogenising trend of sprawl.

References

Batty, M., 2008. The size, scale and shape of cities. *Science*, 319, 769–771. doi:10.1126/science.1151419

Besussi, E., *et al*., 2010. The structure and form of urban settlements. *In*: T. Rashed and C. Jürgens, eds. *Remote sensing of urban and suburban areas*. Dordrecht: Springer, 13–31.

Breheny, M., 1997. Urban compaction: feasible and acceptable? *Cities*, 14 (4), 209–217. doi:10.1016/S0264-2751(97)00005-X

Burgoine, T., Alvanides, S., and Lake, A., 2011. Assessing the obesogenic environment of North East England. *Health and Place*, 17 (3), 738–747. doi:10.1016/j.healthplace.2011.01.011

Burton, E., 2000. The compact city: just or just compact? A preliminary analysis. *Urban Studies*, 37 (11), 1969–2006. doi:10.1080/00420980050162184

Burton, E., 2002. Measuring urban compactness in UK towns and cities. *Environment and Planning B: Planning and Design*, 29, 219–250. doi:10.1068/b2713

CEC, 1999. *European spatial development perspective: towards balanced and sustainable development of the territory of the European Union*. Luxembourg: The European Commission. ISBN 92-828-7658-6, 87.

CEC, 2006a. *Cohesion policy and cities: the urban contribution to growth and jobs in the regions*. Communication from the Commission to the council and parliament, COM (2006) 385, final, 13 July. Brussels, p. 13.

CEC, 2006b. *Urban sprawl in Europe: the ignored challenge*, European Environmental Agency Report No 10. Copenhagen: The European Commission, 60. ISSN 1725-9177.

CEC, 2006c. *Thematic strategy on the urban environment*, 11 November, COM (2005) 718 final. Brussels: The European Commission, 12.

CEC, 2007. *Leipzig charter on sustainable European cities*, 2 May, final draft. Leipzig: The European Commission, 7.

CEC, 2008. *Final statement by the ministers in charge of urban development*, Commission of the European Communities, 25 November, Marseille, p. 7.

CEC, 2010. *Declaration following the Informal ministerial meeting on urban development*, Declaration, Commission of the European Communities, 22 June. Toledo, Spain, p. 17.

CEC, 2011a. *Territorial Agenda of the European Union 2020: towards an inclusive, smart, and sustainable Europe of diverse regions*, 19 May. Hungary, p. 11.

CEC, 2011b. *Mapping Guide for a European Urban Atlas* [online]. Directorate-General for Regional Policy, European Environmental Agency, Commission of the European Communities, p. 1–31. Available from: http://www.eea.europa.eu/data-and-maps/data/urban-atlas/ [Accessed 9 July 2014].

Chin, N.N.G., 2006. *Spatial analysis and the measurement of urban sprawl*. London: Center for Advanced Spatial Analysis and Geography Department, University College London, 346.

CORINE, 2000. Image 2000 and Land Cover 2000 Project [online]. Available from: http://image2000.jrc.it/ [Accessed 2 August 2013].

Davis, C. and Schaub, T., 2005. A transboundary study of urban sprawl in the Pacific coast region of North America: the benefits of multiple measurement methods. *International Journal of Applied Earth Observation and Geoinformation*, 7, 268–283. doi:10.1016/j.jag.2005.06.007

Eurostat, 2004. *Urban audit, methodological handbook*. Luxembourg: Office for Official Publications of the European Communities, 88.

Ewing, R., 1994. Characteristics, causes and effects of sprawl: a literature review. *In*: J. Matzluff, *et al*., eds. *Urban ecology: an international perspective on the interaction between humans and nature*. New York: Springer, 519–535.

Ewing, R., 1997. Is Los Angeles-style sprawl desirable? *Journal of the American Planning Association, Winter*, 63 (1), 107–126. doi:10.1080/01944369708975728

Ewing, R., Pendall, R., and Chen, D. 2002. *Measuring sprawl and its impact*. I 55. Washington, DC: Smart Growth America.

Frenkel, A. and Ashkenazi, M., 2008. Measuring urban sprawl: how can we deal with it? *Environment and Planning B: Planning and Design*, 35, 56–79. doi:10.1068/b32155

Gordon, P. and Richardson, H., 1997. Are compact cities a desirable planning goal? *Journal of the American Planning Association, Winter*, 63 (1), 95–106. doi:10.1080/01944369708975727

Grimm, N., *et al*., 2008. Global change and the ecology of cities. *Science*, 319, 756–760. doi:10.1126/science.1150195

Herold, M., Couclelis, H., and Clarke, K., 2005. The role of spatial metrics in the analysis and modeling of urban land use change. *Computers, Environment and Urban Systems*, 29, 369–399. doi:10.1016/j.compenvurbsys.2003.12.001

Herold, M., Goldstein, N., and Clarke, K., 2003. The spatiotemporal form of urban growth: measurement, analysis and modeling. *Remote Sensing of Environment*, 86, 286–302. doi:10.1016/S0034-4257(03)00075-0

Herold, M., Scepan, J., and Clarke, K., 2002. The use of remote sensing and landscape metrics to describe structures and changes in urban land uses. *Environment and Planning A*, 34, 1443–1458. doi:10.1068/a3496

Hess, G., *et al.*, 2001. Just what is sprawl anyway? *Carolina Planning*, 25 (2), 11–26.

Huang, J., Lu, X., and Sellers, J., 2007. A global comparative analysis of urban form: applying spatial metrics and remote sensing. *Landscape and Urban Planning*, 82, 184–197. doi:10.1016/j.landurbplan.2007.02.010

Jaeger, J., *et al*., 2010. Suitability criteria for measures of urban sprawl. *Ecological Indicators*, 10, 397–406. doi:10.1016/j.ecolind.2009.07.007

Kasanko, M., *et al*., 2006. Are European cities becoming dispersed? A comparative analysis of 15 European urban areas. *Landscape and Urban Planning*, 77, 111–130. doi:10.1016/j.landurbplan.2005.02.003
Longley, P. and Mesev, V., 2000. On the measurement and generalisation of urban form. *Environment and Planning A*, 32, 473–488. doi:10.1068/a3224
Mubareka, S., *et al*., 2011. Development of a composite index of urban compactness for land use modelling applications. *Landscape and Urban Planning*, 103, 303–317. doi:10.1016/j.landurbplan.2011.08.012
Neuman, M., 2005. The compact city fallacy. *Journal of Planning Education and Research*, 25, 11–26. doi:10.1177/0739456X04270466
Prastacos, P., Chrysoulakis, N., and Kochilakis, G., 2012. Spatial metrics for Greek cities using land cover information from the urban atlas. *In*: J. Gensel, D. Josselin, and D. Vandenbroucke, eds. *Proceedings of the AGILE'2012 International Conference on Geographic Information Science, Avignon*, 24–27 April, Multidisciplinary Research on Geographical Information in Europe and Beyond, 261–266.
Razin, E. and Rosentraub, M., 2000. Are fragmentation and sprawl interlinked? North American evidence. *Urban Affairs Review*, 35 (6), 821–836. doi:10.1177/10780870022184697
Rudolf, G., *et al*., 2007. *Smart cities: ranking of European medium-sized cities*, *Final Report* [online]. Center of Regional Science (SRF), Vienna University of Technology, October, Vienna, p. 28. Available from: http://www.smart-cities.eu/download/smart_cities_final_report.pdf. [Accessed 9 June 2014].
Schneider, A., Friedl, M., and Potere, D., 2010. Mapping global urban areas using MODIS 500-m data: new methods and datasets based on 'urban ecoregions'. *Remote Sensing of Environment*, 114, 1733–1746. doi:10.1016/j.rse.2010.03.003
Schneider, A. and Woodcock, C., 2008. Compact, dispersed, fragmented, extensive? A comparison of urban growth in twenty-five global cities using remotely sensed data, pattern metrics and census information. *Urban Studies*, 45 (3), 659–692. doi:10.1177/0042098007087340
Schwarz, N., 2010. Urban form revisited – selecting indicators for characterising European cities. *Landscape and Urban Planning*, 96, 29–47. doi:10.1016/j.landurbplan.2010.01.007
Simpson, H., 1949. Measurement of diversity. *Nature*, 163, 688. doi:10.1038/163688a0
Stathakis, D. and Faraslis, I., 2014. Monitoring urban sprawl using simulated PROBA-V data. *International Journal of Remote Sensing*, 35 (7), 2731–2743. doi:10.1080/01431161.2014.883089
Stathakis, D. and Perakis, K., 2007. Feature evolution for classification of remotely sensed data. *IEEE Geoscience and Remote Sensing Letters*, 4 (3), 354–358. doi:10.1109/LGRS.2007.895285
Stathakis, D., Perakis, K., and Savin, I., 2012. Efficient segmentation of urban areas by the VIBI. *International Journal of Remote Sensing*, 33 (20), 6361–6377. doi:10.1080/01431161.2012.687842
Torrens, P., 2008. A toolkit for measuring sprawl. *Applied Spatial Analysis and Policy*, 1, 5–36. doi:10.1007/s12061-008-9000-x
Tsai, Y., 2005. Quantifying urban form: compactness versus 'sprawl'. *Urban Studies, January*, 42 (1), 141–161. doi:10.1080/0042098042000309748
Wassmer, R., 2000. Urban sprawl in a U.S. metropolitan area: ways to measure and a comparison of the Sacramento area to similar metropolitan areas in California and the U.S., September 8 [online]. CSUS Public Policy and Administration Working Paper No. 2000–03, p. 22. Available from: SSRN: http://ssrn.com/abstract=241975 or http://dx.doi.org/10.2139/ssrn.241975 [Accessed 9 July 2014].
Will, G., 1999. Al gore has a new worry: smart growth to cure suburban sprawl in the newest rationale for government growth. *Newsweek*, February 15.
Wilson, E., *et al*., 2003. Development of a geospatial model to quantify, describe and map urban growth. *Remote Sensing of Environment*, 86, 275–285. doi:10.1016/S0034-4257(03)00074-9