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Suitability criteria for measures of urban sprawl

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ABSTRACT

Rapid increase of urban sprawl in many countries worldwide has become a major concern because of its detrimental effects on the environment. Existing measures of urban sprawl suffer from a confusing variety of differing, and sometimes contradictory, interpretations of the term "urban sprawl". Therefore, results from different studies cannot usually be compared to each other and are difficult to interpret consistently. Every meaningful method to measure the degree of urban sprawl needs to be based on a clear definition of "urban sprawl" disentangling causes and consequences of urban sprawl from the phenomenon of urban sprawl itself, as urban sprawl has differing causes and consequences in different regions and regulatory contexts. This paper contributes to the development of more reliable measures of urban sprawl by providing clarifications to the definition of "urban sprawl" and by developing a set of 13 suitability criteria for measures of urban sprawl.

Our study proceeds in three steps. First, it proposes a clear definition of urban sprawl that is based on an evaluation of existing urban sprawl definitions. Second, it derives from this definition 13 suitability criteria for measures of urban sprawl. These criteria are useful to systematically evaluate the consistency and reliability of existing and future metrics of urban sprawl. The 13 criteria include (1) intuitive interpretation, (2) mathematical simplicity, (3) modest data requirements, (4) low sensitivity to very small patches of urban area, (5) monotonous response to increases in urban area, (6) monotonous response to increasing distance between two urban patches when within the scale of analysis, (7) monotonous response to increased spreading of three urban patches, (8) same direction of the metric's responses to the processes in criteria 5, 6 and 7, (9) continuous response to the merging of two urban patches, (10) independence of the metric from the location of the pattern of urban patches within the reporting unit, (11) continuous response to increasing distance between two urban patches when they move beyond the scale of analysis, (12) mathematical homogeneity (i.e., intensive or extensive measure), and (13) additivity (i.e., additive or area-proportionately additive measure). Third, we illustrate the application of the 13 criteria by systematically assessing three existing measures of urban sprawl. We conclude that suitability criteria help understand the behavior of metrics intended to measure urban sprawl and to identify the most suitable measures. This article is the first part of a set of two papers.

1. Urban sprawl and the need for quantitative measures

Land and soils are finite and their destruction is irreversible within human life spans. Renewable energy supply requires large areas of land, food production necessitates arable and pasture land with suitable soils, and land is also needed for urban-industrial purposes, transport, resource extraction, refuse deposition, and recreation, i.e., all three compete for land. As a consequence, mankind's growing demands for renewable energy, food, and land cannot be circumvented by any form of adaptation. Haber (2007) has called these growing demands the three major "ecological traps" that threaten mankind probably more severely than any other environmental problem, which may allow for some sort of adaptation. If endeavours for promoting sustainable development disregard these three ecological traps, they will inevitably miss their goals. Haber (2007) has warned that land and arable soils are becoming scarcer at an alarming rate, but their increasing scarcity is still underrated. Therefore, much higher efforts are necessary to conserve and properly use land and soils (Haber, 2007).

A major global trend contributing to the competition for land is dispersed urban development. Since the year 2008, half of the planet's population is living in cities and agglomerations, and this

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ratio is increasing (European Environment Agency, 2006). In Europe and North America, the wish of humans to live in a green surrounding, life styles with higher demands regarding dwelling and mobility, the search for inexpensive building lots, relatively low transportation costs, and population growth all contribute to highly dispersed urban development. For example, in Switzerland and Baden-Württemberg, Germany, at least as much land area has been taken up for settlement and transport within the 50 years between 1950 and 2000 as during the preceding 10,000 years before 1950 (Häberli et al., 1991; Jaeger, 2002). As a consequence of dispersed urban development, open landscapes, large un-fragmented wildlife habitats, and areas for recreation and ecological compensation are lost, become fragmented or downsized, and their ecological functions degenerate. Few instruments have been implemented that effectively curtail urban sprawl. The latest report by the European Environment Agency (2006) on the topic of urban sprawl concluded that action is urgently needed, and proposed to elaborate European guidelines to coordinate and monitor urban planning in Europe.

In Switzerland, urban sprawl has been subject to criticism for more than 50 years (e.g., Burckhard et al., 1955; Ewald, 1978; Weiss, 1981). Today, Switzerland is demonstrably committed to the goal of sustainable development by ratifying "Agenda 21" and the Rio Declaration in 1992, and by including it in the revised Federal Constitution in 1999. The Agenda 21 and the Federal Council's Strategy for Sustainable Development demand the identification of sustainability indicators as instruments by which Switzerland's progress in achieving a sustainable development can be monitored. In 2000, three federal offices together launched the Monitoring Sustainable Development project (MONET) to establish a system of indicators for sustainable development in Switzerland (SFSO et al., 2004). The 163 indicators of MONET are nested within 26 "themes", or topics, that encompass social, economic and environmental issues. Of this total, 76 indicators are related to 'ecological responsibility'. 135 indicators are considered currently feasible for implementation. MONET includes an explicit urban sprawl indicator (in addition to the total amount of urban area) but has so far not been able to implement such an indicator: urban sprawl has been marked as "currently not feasible" (SFSO et al., 2004). MONET is representative of many other monitoring systems of sustainable development with regard to using simply the amount of urban area as one indicator and encountering difficulties with including other, more refined measures of urban sprawl.

Even though urban sprawl has been a topic of scientific research for more than 20 years (e.g., Frenkel and Ashkenazi, 2008), meaningful and reliable measures of urban sprawl are still lacking. While there are many metrics available for measuring landscape fragmentation (>20; e.g., Gustafson, 1998; Hargis et al., 1998; Riitters et al., 2004; Sleeman et al., 2005; Kupfer, 2006; Jaeger et al., 2008), relatively few convincing landscape metrics have been proposed for urban sprawl. For example, Besussi and Chin (2003: p. 125, p. 127) stated that "there is little work specifically targeted to measuring sprawl" and, therefore, "further work remains to create useful definitions and indicators of sprawl". One likely reason is that there is considerable debate and confusion about the definition of "urban sprawl" and how it can be measured, which impedes agreement about which of the proposed measures should be used; a similar problem has been observed for landscape fragmentation (Fahrig, 1999; Kupfer, 2006) but the confusion about urban sprawl seems even higher, and the measures that have been proposed (Ewing et al., 2003; Razin and Rosentraub, 2000; Wilson et al., 2003; Davis and Schaub, 2005; Tsai, 2005; Kasanko et al., 2006; Frenkel and Ashkenazi, 2008; Schneider and Woodcock, 2008; Torrens, 2008) focus on many differing dimensions. Torrens (2008) identified eleven characteristics of sprawl and used 42 different metrics related to seven of these characteristics (urban growth, density, social, land-use diversity, fragmentation, decentralization, and accessibility) in his study about Austin, Texas. While we agree that all these characteristics somehow affect or are affected by urban sprawl, the relation of these indicators to urban sprawl is often not clear. As a consequence, we would argue that such a small-shot-charge approach to the phenomenon of urban sprawl adds relatively little to clarify the terminology and the concepts, and can lead to inconsistent results and other problems when comparing results from different studies. Therefore, we advocate a more systematic approach based on suitability criteria (Jaeger, 2000).

This paper has three objectives: (1) to provide a precise definition of the term "urban sprawl", (2) to propose a suite of suitability criteria that captures all relevant requirements that measures of urban sprawl should meet, and (3) to illustrate the application of the suitability criteria through an assessment of a set of existing metrics of urban sprawl using these criteria.

2. Methods

We proceeded in three steps. We first reviewed a representative suite of definitions of "urban sprawl" and of the German notion of "Zersiedelung" from the literature, and based on these definitions, we suggest a clear and precise definition of urban sprawl that serves to infer the relevant information for quantitative measures while disentangling causes and consequences of urban sprawl from the core phenomenon of "urban sprawl". Second, we derived 13 suitability criteria for measures of urban sprawl from this definition. Third, we used the 13 criteria to assess the suitability of three existing measures of urban sprawl. We also used the 13 suitability criteria to develop a new method to measure urban sprawl in a follow-up paper (Jaeger et al., 2009; in the following referred to as "Part II").

3. Definitions of urban sprawl

A number of definitions of urban sprawl have been suggested in the English and German literature (Table 1), but there is no general agreement about what defines urban sprawl (Wilson et al., 2003; Siedentop, 2005). The term "Zersiedelung" was coined already in the 1920ies but was widely used in the German-speaking countries only after the second world war (Akademie für Raumforschung und Landesplanung, 1970). The term was introduced because of a need to find a "(negative) characterization of a complex process that people generally perceived as disturbing" (Akademie für Raumforschung und Landesplanung, 1970: 3863; German original: "(Negativ-)Formulierung für einen komplexen und allgemein als störend empfundenen Vorgang"; translation JAGJ). Most often used descriptors include unbounded development, scattering of settlements, taking-up of open landscape (i.e., outside of the boundaries of a town), area-intensive growth, and leapfrog development (Table 1). Most definitions mix causes and consequences of this pattern of development into the description of the pattern per se which constitutes the core of the definition. The causes include unimpeded and disorganized growth, aimless and unsystematic development of landscapes, demands for living in a green surrounding, the building of second homes, and the search for inexpensive building lots. The consequences include diminution of landscape quality, loss of arable soil, loss of recreation areas, lack of clearly defined open spaces, functional and spatial separation of places for living and working, and large numbers of commuters (Table 1).

One major reason for the prevailing confusion is that many studies used the term to cover causes and consequences as well as different types of urban sprawl (Table 1). To clarify the

Table 1
Definitions of "urban sprawl" from the English and German literature (five examples each; representative selection; modified and extended after Johnson, 2001), and the definition proposed in this paper. (Translations: JAGJ.).

Definition	Source
Sprawl = "on the one hand, the spilling over of urban-type buildings into the suburban and agrarian areas, and on the other hand, the disorganized growth of sporadic beginnings of settlements in agrarian regions (separate farms, houses of farm workers, secondary occupation settlements) as well as in early industrialized or commercially permeated areas where ironworks, foundries and mines served as starting points of such sprawlings. In addition, the term is also applied to the unsystematic positioning of (weekend) houses and groups of houses that are only temporarily occupied outside of closed settlement areas." German original: Zersiedelung = "einerseits das Ausufern städtischer Bebauung in den vorstädtischen und agrarischen Raum hinein, andererseits das ungeregelte Wachstum sporadischer Siedlungsansätze sowohl in Agrargebieten (Einzelhöfe, Landarbeiterwohnungen, Nebenerwerbssiedlungen) wie auch in früh industrialisierten oder gewerblich durchsetzten Räumen, wo Eisenhämmer, Hütten und Bergwerke als Ansatzpunkte derartiger Zersiedelungen dienten. Schliesslich wird der Begriff auch angewendet auf die planlose Ansetzung von nur zeitweilig bewohnten (Wochenend-)Häusern und Häusergruppen ausserhalb geschlossener Siedlungsräume."	Akademie für Raumforschung und Landesplanung (1970: 3863)
Sprawl = "process of the spilling-over of settlement areas and of excessive use of the open landscape by unsystematic, mostly weakly condensed extensions of settlement areas in the fringes of urban agglomerations." German original: Zersiedelung = "Prozeß des Ausuferns der Siedlungsflächen und der übermäßigen Inanspruchnahme der freien Landschaft durch konzeptionslose, meist gering verdichtete Siedlungsflächenerweiterungen in den Randbereichen von Verdichtungsräumen."	Ermer et al. (1994: 119)
Sprawl identified as the combination of three characteristics = "(1) leapfrog or scattered development; (2) commercial strip development; and (3) large expanses of low-density or single-use developments—as well as by such indicators as low accessibility and lack of functional open space".	Ewing (1997: 32)
"Sprawl: the unchecked growth of settlements, taking effect in the area. The danger of sprawl in a landscape is particularly high in the fringe of the large cities, not only through expansive residential building activities, but also through economic institutions that are extensive in area (industrial businesses, airports, etc.). In recent time, sprawl particularly threatens attractive nearby recreational areas through increased building of weekend houses." German original: "Zersied(e)lung: das unkontrollierte, flächenhaft wirkende Wachstum von Siedlungen. Die Gefahr einer Z. der Landschaft besteht vor allem am Rande der grossen Städte, und zwar nicht allein durch eine ausgedehnte Wohnüberbauung, sondern auch durch flächenextensive Wirtschaftseinrichtungen (Industriebetriebe, Flughäfen usw.). Die Z. bedroht in jüngerer Zeit durch einen verstärkten Wochenendhausbau besonders reizvolle Naherholungsgebiete."	Leser and Huber-Fröhli (1997)
Sprawl = "low-density development beyond the edge of service and employment, which separates where people live from where they shop, work, recreate and educate—thus requiring cars to move between zones".	Sierra Club (1999: 1)
Sprawl = "a particular type of suburban development characterized by very low-density settlements, both residential and non-residential; dominance of movement by use of private automobiles, unlimited outward expansion of new subdivisions and leap-frog development of these subdivisions; and segregation of land uses by activity".	USHUD (1999: 33)
"Sprawl is to be understood as the disturbance or destruction of the landscape and of ecosystems by spill-over development of settlements outside of closed built-up areas." German original: "Unter Zersiedelung ist die Beeinträchtigung oder Zerstörung der Landschaft und von Ökosystemen durch ausufernde Siedlungsentwicklung ausserhalb geschlossener Ortschaften zu verstehen."	ARL & VLP (1999: 106)
"Sprawl, is an unplanned, unsystematic, area-intensive outward growth mainly of city-type settlements into the rural space and is a consequence of progressive urbanization. The wish for living in green places, for weekend houses, quickly accessible shopping centers, cheap industrial areas, and transportation infrastructure occupies much space, and if there are no conditions posed by regional planning and environmental protection, then construction will happen at places where it is cheapest. In this way, open spaces, recreational areas, and ecological compensation areas are lost, become dissected or downsized and loose their ecological and socio-economic functions." German original: "Zersiedlung, ist ein ungeplantes, konzeptloses, flächenintensives Hinauswachsen vor allem von städtischen Siedlungen in den ländlichen Raum und ist eine Folge der fortschreitenden Verstädterung und Urbanisierung. Das Bedürfnis nach Wohnen im Grünen, nach Wochenendhäuschen, schnell erreichbaren Einkaufszentren, billigen Industriegebieten und Verkehrsbauten benötigt viel Platz, und ohne Auflagen der Raumplanung und des Umweltschutzes wird dort gebaut, wo es am billigsten ist. Freiflächen, Erholungsgebiete und ökologische Ausgleichsflächen gehen dadurch verloren, werden zerschnitten oder verkleinert und verlieren ihre ökologische, wie auch sozioökonomische Funktionalität."	Landscape Gesellschaft für Geo-Kommunikation (2000–2002: 469)
Sprawl = "the process in which the spread of development across the landscape far outpaces population growth. The landscape sprawl creates has four dimensions: a population that is widely dispersed in low-density development; rigidly separated homes, shops, and workplaces; a network of roads marked by huge blocks and poor access; and a lack of well-defined, thriving activity centers, such as downtowns and town centers. Most of the other features usually associated with sprawl – the lack of transportation choices, relative uniformity of housing options or the difficulty of walking – are a result of these conditions."	Ewing et al. (2002)
"Sprawl is low-density, leapfrog development characterized by unlimited outward extension. In other words, sprawl is significant residential or nonresidential development in a relatively pristine setting. In nearly every instance, this development is low density, it has leaped over other development to become established in an outlying area, and its very location indicates that it is unbounded."	Burchell and Galley (2003: 151)
Urban sprawl is a phenomenon that can be visually perceived in the landscape. The more heavily permeated a landscape by buildings, the more sprawled the landscape. Urban sprawl therefore denotes the extent of the area that is built up and its dispersion in the landscape. The more area built over and the more dispersed the buildings, the higher the degree of urban sprawl. The term "urban sprawl" can be used to describe both a state (the degree of sprawl in a landscape) as well as a process (increasing sprawl in a landscape). The causes, consequences, and assessment of urban sprawl are distinguished from the phenomenon of urban sprawl itself, and therefore are not a part of this definition.	Definition of "urban sprawl" proposed in this paper.

terminology, we suggest to separate the causes and consequences from the phenomenon of urban sprawl itself as much as possible. A quantitative landscape metric is geared to the description of a landscape pattern and is not suited to include the causes and consequences. We therefore propose the following definition, based on the definitions compiled in Table 1 and focussing on the landscape pattern (Fig. 1):

> Urban sprawl is visually perceptible. A landscape suffers from urban sprawl if it is permeated by urban development or solitary buildings. For a given total amount of build-up area, the degree of urban sprawl will depend on how strongly clumped or dispersed the patches of urban area and buildings are; the lowest degree of sprawl corresponds to the situation when all urban area is clumped together into the shape of a circle. The highest possible degree of sprawl is assumed in an area that is completely built over. Therefore, the more urban area present in a landscape and the more dispersed the urban patches, the higher the degree of urban sprawl (see below for more details, e.g., sprawl per capita for including population density).

This definition allows for any particular user-defined delineation of what constitutes "urban areas". These may include various types of settlements and buildings, ranging from places with urban character to villages and even to separate single buildings in the open landscape. In this approach, the buildings' use and style do not matter to their impact on sprawl; all visible buildings contribute to urban sprawl.

In principle, it may be desirable to also include various qualitative characteristics in the calculations of the degree of urban sprawl, e.g., the degree to which new buildings correspond to the traditional structure of the settlements, the degree of correspondence with the character of the landscape, or the height of the buildings. However, in the definition presented above, we deliberately did not include the qualitative aspect of the developed areas (except for the density of inhabitants in a second step, see the presentation of the sprawl-per-capita metric (*SPC*) in Part II). The reasons for this choice are:

(1) The distances between *all* types of buildings are important for determining their dispersion, including the distances between incongruous buildings and buildings of traditional style. Therefore, the locations of the traditional buildings have to be taken into account in the metrics.
(2) A high density of inhabitants is generally considered a positive characteristic that reduces urban sprawl. Therefore, it is not clear if a highrise (or a neighborhood that has high population density) should be weighted more (because it exerts a higher pressure on the landscape than a single-family house) or less (because it houses more people). Thus, a measure of urban sprawl (without including population density yet) and population density should first be calculated separately, and be compared and interpreted only later (see the *SPC* metric presented in Part II).
(3) The identification of the characteristics of buildings (e.g., their height) would require significantly more effort given typically available data. This is especially true for an analysis of historical trends, as this kind of data is generally not available.
(4) The distinction between buildings that fit into a landscape harmoniously and those that do not is often controversial. For example, should aesthetic or ecological criteria be used? Architecture is, to a large part, a matter of taste. Which buildings are assessed as less relevant for sprawl than others would then depend on the observer. Such fuzziness should be avoided in the definition of new metrics of landscape structure (appropriate modification of this sort can still be added later).

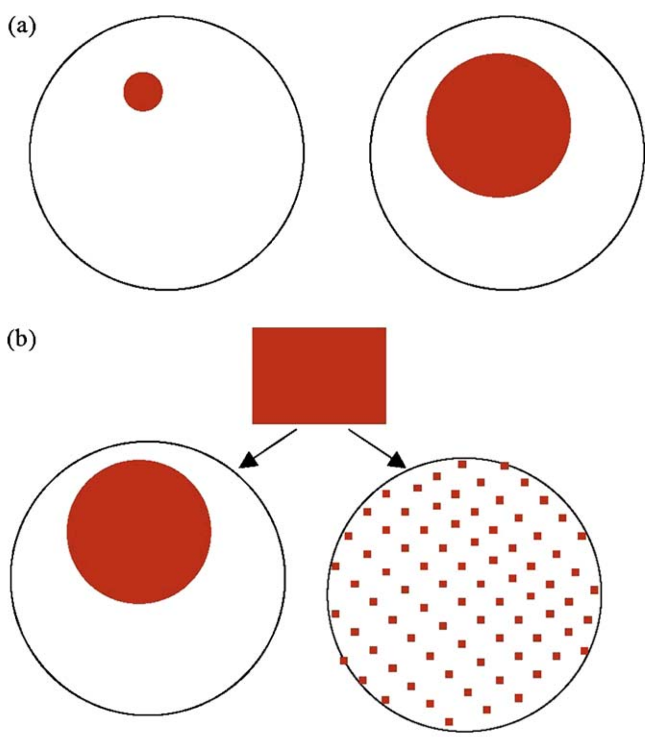

Fig. 1. Illustration of the two major dimensions of urban sprawl: The more urban area present in a landscape and the more dispersed the urban patches, the higher the degree of urban sprawl. (a) Low amount of urban area vs. high amount of urban area; (b) most compact configuration (circle) vs. uniformly dispersed arrangement (i.e., every building is as far away from all other buildings as possible) for a given amount of urban area.

This limitation with regard of the qualitative component of "urban sprawl" needs to be taken into account when interpreting the results of applying new sprawl metrics that are based on this definition (such as those presented in Part II). Even though refinements of the definition to include qualitative characteristics are feasible, they would quickly render the practical implementation and use of the associated metrics difficult.

Throughout the remainder of this paper, we use the term "urban patches" to denote patches of urban area.

4. Requirements for measures of urban sprawl: 13 suitability criteria

Landscape metrics have to meet specific requirements that depend on the particular purposes that the metrics are geared to, and several more general requirements (e.g., their definition needs to be consistent; Jaeger, 2000; Li and Wu, 2004). Suitability criteria specify these requirements explicitly to make them more easily applicable for evaluation and comparison. From the definition given above, we derived 13 suitability criteria for metrics of urban sprawl. The importance of these criteria differs: some are necessary conditions, others denote desirable additional characteristics. Ideally, a metric should meet all criteria.

4.1. Intuitive interpretation

Landscape metrics should be as intuitively sensible as possible, i.e., it should be practicable to gain an intuitive understanding of the concept that is expressed in the mathematical symbols. In case that a measure is not intuitively sensible then checking its suitability is only feasible through complete testing of its behavior, without gaining a more direct, intuitive understanding. An intuitive interpretation is, in principle, not an absolutely necessary condition for practical application of a metric but it is almost indispensable for a convincing interpretation and communication of the results, and for the comparison with other metrics (Jaeger, 2000).

4.2. Mathematical simplicity

Simplicity and the following criterion "modest data requirements" are mostly criteria of efficiency, i.e., for a particular quality of results, the expenditure for performing the calculations should be as low as reasonably possible. Simplicity is also relevant for comprehensibility and implementation, and consequently, for a metric's dissemination and practical use.

4.3. Modest data requirements

All relevant information should be captured in the measures, otherwise they cannot produce valid results. However, the measures should not require more data than what is actually needed for valid results. Reasons for this criterion are efficiency, practical implementation, and dissemination.

4.4. Low sensitivity to very small patches of urban area

The measures should not be too sensitive if small or very small urban patches (e.g., single buildings) are omitted or included in the analysis. The most important reasons for this criterion are that smaller patches are less important than larger patches and that the results should be reproducible by different investigators.

4.5. Monotonous reaction to increases of urban area

Measures of urban sprawl should always increase when new patches of urban development are added to any given landscape, or if existing urban patches are enlarged. This criterion is based on the definition of urban sprawl (see above), which implies that urban sprawl cannot be reduced by adding more urban area.

4.6. Monotonous reaction to increasing distance between two urban patches when within the scale of analysis

When the distance between two urban patches increases while total amount of urban area stays constant then the measures should increase monotonously if the increase of distance occurs within the scale of the analysis (specified by the horizon of perception for the new metrics introduced in Part II). This criterion is also based on the definition of urban sprawl (see above). However, this increase only makes sense up to a certain maximum distance called the horizon of perception, and thus, the increase cannot continue forever (unless the scale of analysis is global). Therefore, an additional criterion is required for larger distances (criterion 11, see below).

4.7. Monotonous reaction to increased spreading of three urban patches

When an urban area is broken up into more and more patches and the patches are spread out in a more dispersed manner (while total amount of urban area stays constant) then the measures should increase monotonously. In particular, if three urban patches are increasingly spread out, the measures should increase (Fig. 2). In other words, the measures should decrease when the patches are moving closer to each other, i.e., are more clumped. This criterion is a necessary requirement. However, it only applies up to a certain maximum distance called the horizon of perception that characterizes the scale of analysis (as in criterion 6).

Fig. 2. Illustration of suitability criterion 7 ("monotonous reaction to increased spreading of three urban patches") using three patches of urban area in a linear configuration. The two outer patches are fixed, and only the patch in the center can be moved to the right or to the left. Every measure of urban sprawl should respond in a monotonous manner to this change in the location of the patch in the center. The degree of urban sprawl is lowest in (a), highest in (b), and intermediate in (c).

4.8. Same direction of the metric's response to the processes in criteria 5, 6 and 7

The reactions of the measure to the processes of criteria 5, 6 and 7 need to be in the same direction (always increasing) to ensure that none of these processes could sometimes be compensated by another one without the user noticing it. This criterion is crucial, and many other measures (such as proximity) do not meet it (see Section 5 below). Therefore, it constitutes a separate criterion.

4.9. Continuous reaction to the merging of two urban patches

When two urban patches are merging while total amount of urban area stays constant then the decrease of the measures needs to be continuous (i.e., no jumps). This is a required characteristic.

4.10. Independence of the metric from the location of the pattern of urban patches within the reporting unit

Imagine a landscape with a certain pattern of urban patches. When a reporting unit is chosen (sufficiently large, of a particular size) then there may be different positions of the reporting unit possible that would include the entire urban pattern. The degree of urban sprawl should not depend on the location of the pattern of urban patches within the reporting unit because the choice of the location of the frame applied to investigate the landscape should not change the result. Urban sprawl is a function of the dispersion and the amount of urban areas and, therefore, should not differ if the entire pattern is moved around in the landscape (i.e., in the frame). However, the measure will likely depend on the size of the reporting unit.

4.11. Continuous reaction to increasing distance between two urban patches when they move beyond the scale of analysis

When the distance between two urban patches is larger than the scale of analysis, their distance should not influence the metric's value any more. When the distance between the patches crosses the threshold (from distances lower to larger than the scale of analysis) then the metrics should respond continuously (no jumps). This is a required condition because the metrics would otherwise be too sensitive to inter-patch distances to be interpreted unambiguously.

Table 2
Examination of three measures (amount of urban area, proximity, and contagion) with regard to the 13 suitability criteria for metrics of urban sprawl (+++ = very good, ++ = satisfying or good, + = slightly fulfilled, – = not fulfilled).

Suitability criteria	Assessment of the measures					
	Amount of urban area (A_{urb})		Proximity (*PROX*)		Contagion (*CONT*)	
	Suitability	Explanation	Suitability	Explanation	Suitability	Explanation
1. Intuitive interpretation	+++	A_{urb} is straightforward to understand.	+	*PROX* increases with increasing size of neighboring patches and their increasing nearness; however, it is unreasonable that increasing nearness would lead to an infinite contribution (due to $1/h_{is}^2 \to \infty$ when $h_{is} \to 0$); see also criterion 9.	+	*CONT* seems intuitive because it is an entropy of patch type frequencies combined with adjacencies to the same and other patch types, but it is unclear how its value is influenced by the choice of a particular pixel raster and values based on different rasters cannot be compared.
2. Mathematical simplicity	+++	A_{urb} is mathematically very simple.	+++	*PROX* is mathematically very simple.	+++	*CONT* is mathematically easy to calculate (once a pixel raster has been chosen).
3. Modest data requirements	+++	A_{urb} has low data needs. Maps of the areas classified as "urban" are sufficient.	+++	*PROX* has low data needs (sizes of urban patches and their mutual edge-to-edge distances).	+++	*CONT* has low data needs (counts of adjacencies in the raster).
4. Low sensitivity to very small patches of urban area	+++	The contribution of each patch of settlement area to A_{urb} is proportional to its size; smaller patches have less influence on the value of the metric.	–	Even very small patches have a large influence on *PROX* when they are located close to another patch (because of the factor $1/h_{is}^2$); see also criterion 9.	+++	The contribution of each patch is proportional to its size; i.e., smaller patches have less influence.
5. Monotonous reaction to increases in urban area	+++	When new urban areas are added to a landscape, the value of A_{urb} always increases.	–	*PROX* can increase or decrease when new urban areas are added to the landscape (bacause of the factor $1/n$ and n can increase or decrease when urban areas are added).	–	*CONT* can increase or decrease when new urban areas are added to the landscape (see text).
6. Monotonous reaction to increasing distance between two urban patches when within the scale of analysis	–	A_{urb} does not react to changes in the distance between two urban patches.	+++	*PROX* always decreases when the distance h_{is} between two patches increases.	–	*CONT* does not react to changes in the distance between two urban patches (as numbers of adjacencies remain the same).
7. Monotonous reaction to increased spreading of three urban patches	–	A_{urb} is not sensitive to this change in configuration.	++	*PROX* is lowest when the patches are spread evenly and assumes very high values when two patches come very close (but behaves discontinuously when they merge, see criterion 9).	–	*CONT* does not react to increased spreading (because the numbers of adjacencies of each type do not change).
8. Same direction of the metric's responses to the processes in criteria 5, 6 and 7	–	A_{urb} responds differently to criterion 5 than to criteria 6 and 7.	–	*PROX* can react in opposite directions in 5 and 6/7 (and within 5).	–	*CONT* reacts in both directions within 5 and does not react to 6 and 7.
9. Continuous reaction to the merging of two urban patches	+++	A_{urb} is not sensitive to this change in configuration.	–	*PROX* approaches infinity (because of the factor $1/h_{is}^2$) and then "jumps" to 0; i.e., it is discontinuous.	++	*CONT* increases or decreases at the moment of merging (but continuous approach of two patches cannot be represented very well in pixel rasters).

10. Independence of the metric from the location of the pattern of urban patches within the reporting unit	+++	A_{urb} is not sensitive to the location of urban areas in the landscape.	+++	*PROX* does not depend on the location of the pattern of urban patches in the landscape (only on the distances between the patches).	+++	*CONT* does not depend on the location of the pattern of urban patches in the landscape (as long as the numbers of adjacencies do not change).
11. Continuous reaction to increasing distance between two urban patches when they move beyond the scale of analysis	+++	A_{urb} is not sensitive to this change in configuration (and does not even include a parameter that would represent the scale of analysis).	–	*PROX* does not react continuously when the distance h_{is} exceeds the search radius *r* but "jumps" to 0.	+++	*CONT* is not sensitive to this change in configuration (and does not even include a parameter that would represent the scale of analysis).
12. Mathematical homogeneity (i.e., intensive or extensive measure)	+++	A_{urb} is an extensive measure.	+++	*PROX* is an intensive measure (when appropriate boundary corrections are applied).	+++	*CONT* is an intensive measure (when pixel pairs at the boundary are taken into account appropriately).
13. Additivity (i.e., additive or area-proportionately additive measure)	+++	A_{urb} is an additive measure.	–	*PROX* is neither additive nor area-proportionately additive.	–	*CONT* is neither additive nor area-proportionately additive.

4.12. Mathematical homogeneity (i.e., intensive or extensive measure)

The following two characteristics are simple mathematical properties (cf., Chandler, 1987, pp. 22–25, Legendre and Legendre, 1998, p. 31) transferred to landscape pattern metrics with valuable consequences for the use of the measures (Jaeger, 2000). Being *intensive* means remaining constant when the analysed region is being enlarged but keeping its spatial pattern. This property is a convenient characteristic for the interpretation of a measure as quantifying an *intrinsic* property of the landscape. If the measure increases by the same factor the region is multiplied by, it is called *extensive*. In other words, a landscape metric, say *F*, is called intensive if $F(\lambda \times \Phi) = F(\Phi)$, and it is called extensive if $F(\lambda \times \Phi) = \lambda \times F(\Phi)$ (for all area configurations Φ and all $\lambda \in$ N with $\lambda \times \Phi$ defined as the multiplication of the region represented by Φ in the same spatial arrangement of patches, e.g., for a landscape with one town and no other building around it, a multiplication by $\lambda = 9$ results in a nine-fold repetition of the original landscape). To an extensive quantity, one can always find a corresponding intensive quantity by dividing by the size of the landscape A_t (and *vice versa*).

4.13. Additivity (i.e., additive or area-proportionately additive measure)

Being *additive* means that the value for the combination of two or more reporting units equals the sum of the values of the reporting units. Being *area-proportionately additive* means that a metric characterizes a landscape independently of its size and that it can be calculated for the combination of two or more regions from the values of the regions in the same way that temperature or the concentration of a liquid is determined: When two liquids are mixed, the concentration of the mixture becomes

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

with V_i and c_i denoting the volumes and concentrations. This mathematical characteristic is the most straightforward counterpart of what one intuitively understands as an intrinsic property. It coincides with the most intuitive expectation for the value of a combination of reporting units: each part contributes proportionally to its size, even if each part has a different spatial structure. This characteristic makes a measure particularly helpful for comparing the degree of sprawl of regions of different sizes, and in assessing the influence of parts of a region to the degree of sprawl of the entire region. The characteristics of being extensive or intensive, additive or area-proportionately additive, are interrelated: Every additive quantity is extensive, every area-proportionately additive quantity is intensive. However, the reverse generally does not hold. For example, according to thermodynamics, entropy is a quantity which is extensive but not additive (Straumann, 1986, p. 38). Average patch size is an example of an intensive measure that is not area-proportionately additive.

To fully understand the behavior of measures, they need to be systematically checked according to these suitability criteria. These tests can use simple patterns of urban patches.

5. Illustration of the suitability criteria

We illustrate the use of the 13 criteria by applying them to a set of existing measures of urban sprawl. The simplest measure is the amount of urban area. Even though the amount of urban area is an important component of urban sprawl and widely used, it is not sufficient to measure urban sprawl because it does not include information about the spatial arrangement of urban areas. It meets criteria 1–5 and 9–13, but it does not meet criteria 6–8 (Table 2).

Various other measures have been suggested to quantify certain aspects of urban sprawl (e.g., Ewing, 1997; Ewing et al., 2002; Razin and Rosentraub, 2000; Wilson et al., 2003; Davis and Schaub, 2005; Frenkel and Ashkenazi, 2008; Torrens, 2008). For example, Razin and Rosentraub (2000) used three measures of density to measure residential sprawl: (1) the percentage of dwellings in single-unit detached houses, (2) population density (per square kilometer), and (3) housing units per square kilometer. However, these are attributes of urban areas regardless of their relative location to other urban areas. Therefore, they are more useful to characterize various aspects associated with urban sprawl rather than the spatial arrangement of urban development. Davis and Schaub (2005) used three different measures: (1) "impervious metric", i.e., change in the amount of built surface per capita of population increase (using proportion of impervious surface estimated from satellite imagery), (2) "neighborhood metric", i.e., population density in cells of a $30\,\text{m} \times 30\,\text{m}$ grid (in comparison with the threshold in population density of 12 people per acre at which public transportation becomes viable), and (3) "permit metric", i.e., annual number of residential building permits for new construction (within and outside of urban growth boundaries). These metrics also characterize urban areas regardless of their relative location to each other, and therefore, they do not quantify the spatial arrangement of urban areas (other than their location inside or outside of urban growth boundaries). Overall, these measures are variations of the amount and intensity of the use of urban areas.

In contrast, two metrics that are affected by the spatial arrangement of the urban areas are proximity and contagion. The proximity metric (Whitcomb et al., 1981; Gustafson and Parker, 1992, 1994) takes into account the sizes of patches and the distances to their neighboring patches (within the search radius r):

$$PROX = \frac{1}{n}\sum_{i=1}^{n}\sum_{\substack{h_{is}<r \\ (s\neq i)}} \frac{A_s}{h_{is}^2} = \frac{1}{n}\sum_{i=1}^{n} PI_i \text{ with } PI_i = \sum_{\substack{h_{is}<r \\ (s\neq i)}} \frac{A_s}{h_{is}^2}, \qquad (1)$$

where h_{is} denotes the distance between patch i and patch s ($s \neq i$; measured from edge to edge, regardless of the presence of other patches located between the two edges), A_s denotes the size of patch s located closer to patch i than r, n is the total number of patches in the landscape, and r is the search radius within which patches around patch i are included, i.e., r specifies the scale of analysis chosen by the researcher.

Some authors have used A_s/h_{is} instead of A_s/h_{is}^2 (Gustafson and Parker, 1992); the assessment given below (and in Table 2) applies to both versions of *PROX*. *PROX* meets criteria 1–3, 6–7, 10 and 12 but does not meet criteria 4–5, 8–9, 11 and 13 (Table 2).

There are two major issues with *PROX*. First, the value of *PROX* can increase or decrease when new urban areas are added to the landscape (criterion 5). Therefore, the proximity metric does not meet criterion 8, either, because an increase in the value of *PROX* can be produced by a decrease in the distance between patches (i.e., lower degree of sprawl) and by an increase of urban area (i.e., higher degree of sprawl) (Table 2). Second, it produces "jumps" when two or more patches are merging, i.e., criterion 9 is violated (see also Jaeger, 2002: 124–126). Replacing $\sum_{h_{is}<r} A_s/h_{is}^2$ by $\sum_{s=1}^{n} A_s\, e^{-h_{is}/r}$ (where n is the total number of patches in the landscape) in the formula of *PROX* (and including the case $i = s$) would make much more sense, because this new version would meet criterion 9 (as shown in Jaeger, 1999: 495–497). This version would also meet criteria 4 and 11 (and would meet criterion 1 to a higher degree). However, this new version would still violate criteria 5, 8 and 13.

The contagion metric (Riitters et al., 1996; McGarigal et al., 2002) has often been used as a measure of relative spatial scattering based on a per-pixel land-use map. It is calculated by the formula

$$CONT = \left[1 + \frac{\displaystyle\sum_{i=1}^{m}\sum_{j=1}^{m} P_i \frac{g_{ij}}{\sum_{k=1}^{m} g_{ik}} \cdot \ln\left(P_i \frac{g_{ij}}{\sum_{k=1}^{m} g_{ik}}\right)}{2\ln(m)}\right] \times 100\% = \left[1 + \frac{\displaystyle\sum_{i=1}^{m}\sum_{j=1}^{m} \frac{g_{ij}}{n_{\text{pp}}} \ln\left(\frac{g_{ij}}{n_{\text{pp}}}\right)}{2\ln(m)}\right] \times 100\% \qquad (2)$$

where m denotes the total number of patch types potentially present in the landscape, P_i denotes the proportion of the landscape occupied by patch type i, g_{ij} is the number of ordered adjacencies between pixels of patch types i and j (including the case $i = j$), and n_{pp} is the total number of ordered pixel pairs in the landscape (=total number of ordered adjacencies). Contagion has been used to measure urban sprawl by Torrens (2008). (Note that the indices in the formula for *CONT* given by Torrens (2008) are mixed up.) The range of *CONT* is 0–100%. Small values of contagion close to 0 result when the patch type frequencies are more or less equal and the frequencies of same-type adjacencies are about the same as the frequencies of different-type adjacencies, i.e., equal proportions of all pairwise adjacencies (Riitters et al., 1996). High contagion is usually interpreted as pixels having the *same* patch type tend to be adjacent, i.e., that clumping is present, because contagion is strongly driven by the relatively higher frequencies of same-type pixel pairs. The highest value of 100% is reached when the landscape consists of one single patch (only one patch type present). However, as discussed clearly by Riitters et al. (1996), contagion is actually affected by relatively higher frequencies of adjacency between *any* two patch type pairs, even when $i \neq j$. For example, relatively frequent pairing of patch types "streams" and "riparian vegetation" will increase the calculated value of contagion even in the absence of real clumping. In addition, contagion is affected by variation in patch type frequencies. Therefore, higher values of *CONT* may result from (1) real tendencies for clumping, (2) from high frequencies of adjacency between two different classes, or (3) from variations in patch type frequencies (Riitters et al., 1996). This behavior of the *PROX* metric makes an unambiguous interpretation of its value difficult to achieve when no additional information about the landscape pattern is given.

For applying *PROX* to the analysis of urban sprawl, two land-use types need to be distinguished (urban, non-urban), i.e., $m = 2$, and the denominator assumes the value $2\ln(2) = 1.3863$ which is the maximum entropy when there are two patch types present in the landscape. The systematic assessment based on the 13 suitability criteria shows that *CONT* meets criteria 1–4 and 9–12, but does not meet criteria 5–8 and 13 (Table 2).

This result is not surprising given that there are two obvious issues with contagion:

(1) When the per-pixel map is "inverted", i.e., all urban pixels are transformed to non-urban pixels and *vice versa*, the value of *CONT* stays the same because the formula of *CONT* treats all land-use types equally. This is problematic because the degree

of urban sprawl is generally not the same in both cases, e.g., when the amount of urban pixels is higher in one of the two cases. This is related to criterion 5: *CONT* can increase or decrease when new urban areas are added to the landscape, e.g., *CONT* equals 100% for an entirely non-urban landscape, decreases to 0 when urban pixels are added to the landscape until $P_{\text{urban}} = P_{\text{non-urban}} = 50\%$ and the frequencies of adjacency are equal, and then again increases to 100% for an entirely urban landscape.

(2) The value of *CONT* changes when the size of the pixels used to calculate *CONT* is changed (i.e., change of resolution) because the definition of *CONT* is based on pixels, and to our knowledge, there is no generalized definition of contagion available that could be applied to continuous maps of urban patches. Therefore, values of *CONT* that are based on different pixel sizes cannot be compared to each other. This issue is related to criterion 9 in that pixel-based metrics cannot very well represent a continuous approach and the merging of two patches.

6. Discussion and conclusion

There are two contrary trends in the development of landscape metrics: *index differentiation* in order to more precisely distinguish between specific aspects of landscape structure, and *concentration* in order to select a few metrics that represent groups of highly correlated measures (e.g., Riitters et al., 1995). Both trends have their merits (Riitters et al., 1996); however, only a limited number of indicators can be reported in monitoring systems. Therefore, the selected measures should focus on the core of the phenomenon that is intended to be monitored as precisely as possible. For urban sprawl, the ideal case would be that one indicator quantifies the degree of urban sprawl, while a set of additional indicators measure relevant causes, consequences, and attributes of urban sprawl.

The 13 suitability criteria assist in understanding the behavior of metrics and in identifying the most suitable measures. They are also useful to sharpen the conception of "urban sprawl". The importance of the 13 criteria differs: some are necessary requirements while others are desirable (see Section 4). Suitability criteria for landscape metrics have been used before. Jaeger (2000) suggested eight suitability criteria for measures of landscape fragmentation. Six of these criteria are the same as criteria 1–4 and 12–13 discussed in this paper. The other two criteria are "monotonous reaction to different fragmentation phases (i.e., perforation, incision, dissection, dissipation, shrinkage and attrition)", and "detection of structural differences (such as bundling of transport infrastructure)". Criteria 5–8 for measures of sprawl (Table 2) are similar to the requirement of fragmentation metrics to respond in a monotonous manner to different fragmentation phases. Criteria 9–11 in this paper are not related to the suitability criteria for fragmentation metrics.

The application of the 13 criteria demonstrated that A_{urb}, *PROX*, and *CONT* are limited in their suitability as measures of urban sprawl. These metrics may be useful to quantify certain attributes of the pattern of urban development in a landscape, but their interpretation should always be informed by the limitations of these measures.

A comprehensive comparison of all existing measures of urban sprawl based on the 13 suitability criteria is beyond the scope of this paper, but should be conducted in a subsequent study to better understand their behavior and to reveal their strengths and weaknesses. Table 2 illustrates how such a comparison would proceed. We are not aware of any existing measures of urban sprawl that would meet all 13 suitability criteria developed in this paper.

The three metrics shown as examples demonstrate that a clear understanding of the behavior of a metric is indispensable for assessing its suitability as a measure of urban sprawl. The use of contagion (*CONT*) by Torrens (2008), appears to be an example of an interpretation of the contagion metric that is insufficiently supported. Torrens (2008) used 12 land-use types and compared the values of *CONT* for three points in time, which were 80.78% (1990), 70.23% (1995) and 71.37% (2000). His interpretation was that the observed reduction in *CONT* "suggests that the city became 10% more fragmented from 1990 to 1995 (recall that contagion reaches 0% when there is maximum fragmentation of *pixels* in the landscape)." However, this reduction can also be a result of two other processes: reduction in frequencies of adjacency between different land-use types, and variations in land-use type frequencies (Riitters et al., 1996, as discussed above). To support his interpretation, Torrens would have to explicitly consider by how much these two processes have influenced the value of *CONT*. Without such an explanation, his interpretation is not reliable. Li and Wu (2004) have summarized the dangers of using landscape metrics when their behavior is not well understood.

When a metric treats all patch types equally, as *CONT* does, this should be taken as a warning signal. For example, when a landscape is "inverted" (i.e., all urban patches are transformed into non-urban patches and *vice versa*) then the value of the metric does not change even if there is now much more urban area.

The modification of the *PROX* metric suggested in this paper has several advantages. The modified version of *PROX* meets more criteria than the original version, but it still violates criteria 5 and 8, which are essential suitability criteria for measures of urban sprawl.

This article is the first part of a set of two publications. Part II proposes a new method to measure urban sprawl that meets all 13 suitability criteria.

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