Spatiotemporal patterns of urbanization in three Swiss urban agglomerations: insights from landscape metrics, growth modes and fractal analysis

Martí Bosch · Rémi Jaligot · Jérôme Chenal

Abstract

Context Urbanization is the most important form of landscape change and is increasingly affecting biodiversity and ecosystem functions. Understanding how landscape patterns change in space and time is central to the evaluation of the environmental impacts of urbanization.

Objectives This research explores the spatiotemporal patterns of land use change in the Swiss urban agglomerations of Bern, Lausanne and Zurich at two characteristic spatial extents, and compares them to prominent hypotheses of urbanization patterns.

Methods For each urban agglomeration, four temporal snapshots from 1980 to 2016 have been derived from the land use inventory of the Swiss Federal Statistical Office. Fractal analysis of the area–radius relationship of urban land is used to separate each agglomeration into two characteristic spatial extents, according to the distance of the city center, namely the inner and outer zones. The landscape metrics and growth modes are then computed at such extents.

Results The time series of landscape metrics and growth modes reveal fairly different patterns when computed in the inner and outer zones respectively. Bern and Lausanne exhibit mostly traits of coalescence stages at the inner zone while displaying many characteristics of diffusion in the outer zone. In contrast, the trends of observed in the inner and outer zones of Zurich are both reminiscent of a coalescence stages.

Conclusions Fractal analysis can be a useful approach to detect characteristic extents of urban agglomerations at which distinct spatiotemporal patterns might be observed. Current models of urbanization patterns should incorporate the notion of characteristic extents more explicitly.

Keywords Urbanization · Land use change · Spatial pattern analysis · Landscape metrics · Diffusion and coalescence hypothesis · Urban growth modes · Fractals · Scaling · Complexity

Introduction

The last centuries have seen an unprecedented growth of urban areas, which has resulted in dramatic conversion of natural land and profound changes in landscape patterns and the ecosystem functions that they support (Alberti 2005). The combination of current demographic prospects and the observed
trends of decreasing urban densities suggest that the global amount of land occupied by cities might increase threefold by 2030 (Angel et al. 2005). Although the land use and land cover changes associated to urbanization have occurred on less than a 3% of the earth’s terrestrial surface, the environmental footprint of cities has significant implications at the global scale, for their functioning produces 78% of the earth’s greenhouse gases (Grimm et al. 2008). Given that urbanization will continue to be a major form of landscape change in the next decades, quantifying urban landscape patterns in space and time is crucial to understand the driving forces and ecological impacts of urbanization (Wu 2014).

Recent decades have witnessed an increasing number of studies of the spatiotemporal patterns of land use change associated to urbanization (Dietzel et al. 2005; Seto and Fragkias 2005; Schneider and Woodcock 2008; Jenerette and Potere 2010; Wu et al. 2011; Li et al. 2013; Liu et al. 2016; Nong et al. 2018). Building upon previous ideas of urban growth phases and wave-like urban development, initial attempts to synthesis suggested that urbanization can be characterized as a two-step alternating process of diffusion and coalescence (Dietzel et al. 2005; Schneider and Woodcock 2008). Nonetheless, subsequent studies challenged the empirical validity of such hypothesis. The thorough study of Jenerette and Potere (2010) examined the spatiotemporal patterns of land use change of a sample of 120 cities distributed throughout the world from 1990 to 2000, and determined that overall, urbanization leads to fragmented landscapes with more complex and heterogeneous structures. Similarly, in a comparative analysis of the metropolitan regions of Phoenix and Las Vegas, Wu et al. (2011) revealed that throughout the twentieth century, the two agglomerations did not display signs of distinct urban growth phases, but instead showed a strikingly similar trend towards a landscape that is more diverse in land use, fragmented in structure and complex in shape. Subsequently, Li et al. (2013) determined that the two-phase diffusion and coalescence model can be over-simplistic and that urbanization might be better characterized by means of three growth modes, namely infilling, edge expansion and leapfrogging, which operate simultaneously while alternating their relative dominance. Such results were confirmed by the thorough study of 16 world cities over the 1800–2000 period by Liu et al. (2016), who further resolved that urbanization generally leads to an increasingly diverse and complex landscape.

Nevertheless, such models of urbanization missappreciate the way in which contemporary cities are multi-scaled systems, organized in different levels that show its own characteristic spatiotemporal patterns (Batty 2005, 2008; White et al. 2015). While both the diffusion and coalescence model of Dietzel et al. (2005) and the three growth modes model of Li et al. (2013) make use of a hierarchical framework and evaluate the spatial patterns at different extents, the choice of such extents is not based on quantitative criteria and neglects the characteristic scales of complex systems such as urban patterns. Despite the apparent complexity and diversity of urban forms, cities comply with well-defined principles of spatial organization, which can be characterized quantitatively by means of fractal geometry. A remarkable regularity is found in the relationship between the total built-up area and the distance from the city center, which has been shown to empirically follow a scaling law with very stable exponents for a wide variety of cities (Frankhauser 1994; Batty and Longley 1994). In a thorough examination of a global sample of cities, Frankhauser (1994) noted the existence of a kink in the area–radius relationship, which reveals a change on the spatial structure of cities at a certain distance from their center. The same pattern was found in the urban cellular automata simulations of White and Engelen (1993), suggesting that the area–radius scaling could be better approximated through two scaling exponents, a first steeper one for small distances to the city center, reflecting an inner zone where urbanization was essentially complete, and a second lower slope for the outer zone that is still undergoing urbanization.

The objective of this study is therefore to build upon fractal analysis in order to enlighten the current hypotheses of the spatiotemporal patterns of urbanization. More precisely, the area–radius relationship will be used to detect characteristic extents in urban agglomerations, such as the inner and outer zones reviewed above. Thereupon, the time series of landscape metrics and growth modes will be computed at such extents in order to evaluate the degree to which the spatiotemporal patterns of urbanization operate differently at each scale. The results will serve assess the validity of the diffusion and coalescence and three growth modes hypothesis and provide critical insights.
into how they could be revised from a multi-scale perspective.

Materials and methods

Study area

Switzerland is a highly developed country in central Europe, with a population distributed into several interconnected mid-sized cities and a large number of small municipalities. Mainly because of the country’s topography, most urban settlements are located in its Central Plateau region, which accounts for about one third of the total Swiss territory, (42,000 km²) and is highly urbanized (450 inhabitants per km²). The Central Plateau is characterized by elevations that range from 400 to 700 m, a continental temperate climate with mean annual temperatures of 9–10 °C and mean annual precipitation of 800–1400 mm, and a dominating vegetation of mixed broadleaf forest.

In line with the country’s federalist government structure, the Swiss spatial planning system is distributed between the federal state, the 26 cantons and 2495 municipalities. The federal state specifies the framework legislation and coordinates the spatial planning activities of the cantons, while cantons check the compliance of municipal development plans with cantonal and federal laws. With some exceptions, municipal administrations are in charge of their local development plans, namely the land use plan and building ordinance, and might therefore be viewed as the most important spatial planning entities. While the Federal Statue on regional planning of 1979 limited the number of new buildings constructed outside the building zones, built-up areas have since increased continuously, mainly because the municipalities can designate new building zones almost entirely autonomously (Jaeger and Schwick 2014). A major revision of the Federal Statue was accepted in 2013, which limits the amount of building zones that municipalities can designate and encourages infill development and densification by means of tax incentives. Forecasts based on the current urbanization trends predict significant increases of urban land use demands over the next decades, mostly at the expense of agricultural land located at the fringe of existing urban agglomerations (Price et al. 2015).

Given that a significant part of the cross-border urban agglomerations of Geneva and Basel (the second and third largest in Switzerland) lie beyond the Swiss boundaries (SFSO 2014), in order to ensure coherence of the land use/land cover data, this study comprises only three of the five largest Swiss urban agglomerations, namely Bern, Lausanne and Zurich (SFSO 2018). As shown in Fig. 1, the three agglomerations have undergone important population growth over the last 30 years, especially during the most recent years and at the agglomeration extent. With a total population over 1.3 million and land area of 1305 km² (1038 hab/km²), Zurich is the largest Swiss urban agglomeration. As a leading global city and one of the world’s largest financial centers, Zurich has the country’s largest airport and railway station, and also hosts the largest Swiss universities and higher education institutions. Bern is the capital of Switzerland and fourth most populous urban agglomeration in Switzerland, with a total population of 410,000 inhabitants and occupying a land area of 773 km² (537 hab/km²). As the fifth largest Swiss urban agglomeration and the second most important student and research center after Zurich, the Lausanne agglomeration has a total population of 409,000 inhabitants over a land area of 773 km² (537 hab/km²). Given its larger population growth rate, Lausanne is likely to soon surpass Bern and become the fourth largest urban agglomeration in Switzerland. Overall, the three urban agglomerations are characterized by a pervasive public transportation system and a highly developed economy, with a 85% of the employment devoted to the tertiary sector.

Data sources

The Swiss Federal Statistical Office (SFSO) provides an inventory of land statistics datasets (SFSO 2017), namely a set of land use/land cover maps for the national extent of Switzerland, which comprise 72 base categories. Four datasets have been released for 1979/85, 1992/97, 2004/09 and 2013/18, at a spatial resolution of one hectare per pixel. The pixel classification is based on computer-aided interpretation of satellite imagery, which includes special treatment

1 The exact dates of each surveying period 1979/85, 1992/97, 2004/09 and 2013/18 are determined according to the production process of the national maps and vary across the Swiss territory (SFSO 2017).
and field verification of pixels where the category attribution is not clear.

The SFSO land statistics datasets have been used to produce a series of categorical maps for each urban agglomeration and time period. In order to process the SFSO datasets in an automated and reproducible manner, an open source reusable toolbox to manage, transform and export categorical raster maps has been developed in Python (Bosch 2019b). The boundaries of each urban agglomeration have been adopted from the definitions provided also by the SFSO (2014), which comprise multiple municipalities and have been established in consideration of population density, proximity between centers, economic activities and commuting behavior. As stated above, Geneva and Basel are excluded from this study because a significant portion of their urban agglomeration lies beyond the extent covered by the SFSO land statistics inventory, namely the administrative boundaries of Switzerland. The spatiotemporal evolution of the urban footprint for the three selected urban agglomerations (i.e., Bern, Lausanne and Zurich) over the study period (i.e., 1980–2016) is displayed in Fig. 2.

Area–radius scaling in urban agglomerations

In order to quantitatively detect characteristic spatial extents of urban agglomerations, the relationship between the built-up area and the distance form the main city center will be evaluated from the perspective of fractal geometry. If cities are to be considered fractal objects, such relationship should follow a scaling rule of the form (Mandelbrot 1983):

\[ A(r) \sim r^D \]  

where \( A \) denotes the total area of the urban built-up extent that lays within a distance \( r \) from the city center, and \( D \) corresponds to the radial dimension, analogous to the fractal dimension of two-dimensional complex objects such as Sierpinski carpets.

With the aim of assessing whether the urban agglomerations follow the bi-fractal city model suggested by White and Engelen (1993), a piecewise linear regression with two segments will be compared to that of a simple linear regression. The optimal breakpoint of the two-segment regression, namely, the breakpoint location that minimizes the sum of squared residual will be computed with the `pwlf` Python library, which is based on the differential evolution optimization algorithm (Storn and Price 1997). In this context, such breakpoint corresponds to the kink in the area–radius scaling noted by Frankhauser (1994), namely the radial distance to the city center at which cities show a distinct spatial structure that is less space-filling. Thereupon, three spatial extents will be considered in the analysis of the spatiotemporal

---

\(^2\) See https://github.com/cjekel/piecewise_linear_fit_py.
patterns of urbanization. The first extent corresponds to the whole urban agglomeration defined by the SFSO (2014), which is described in the foregoing section. The second and third extents will be derived from the location of the kink, i.e., the breakpoint of the two-segment regression of the area–radius relationship. More precisely, in line with White and Engelen (1993), the second extent will be defined as the inner zone, i.e., a circle with with the city core as center and the breakpoint distance as radius, while the third extent will be defined as the outer zone, i.e., the area that lies outside the inner zone circle and the agglomeration boundaries.

**Fig. 2** Evolution of urban patches of the three urban agglomerations throughout their respective periods of study. The times $t_0$, $t_1$, $t_2$ and $t_3$ correspond to 1981, 1993, 2004 and 2013 for Bern; 1980, 1990, 2005 and 2014 for Lausanne and 1982, 1994, 2007 and 2016 for Zurich

Quantifying spatiotemporal patterns of urbanization

*Time series of landscape metrics*

While a plentiful collection of landscape metrics can be found in the literature, many of them are highly correlated with one another. As a matter of fact, Riitters et al. (1995) found that the characteristics discerned by 55 prevalent landscape metrics could be reduced to only 6 independent factors. On the other hand, landscape metrics can be very sensitive to the resolution and the extent of the maps. However, several metrics empirically exhibit consistent
responses to changing scales that conform to predictable scaling relations (Wu et al. 2002; Wu 2004). Based on such remarks, and in order to enhance comparability with other studies, ten landscape metrics have been selected for the present study, whose details are listed in Table 1.

While complying with the FRAGSTATS v4 definitions (McGarigal et al. 2012), the landscape metrics have been computed with the open source library PyLandStats (Bosch 2019a). Like in most of the related studies, the categorical maps have been reclassified into urban and natural classes, and the metrics have computed at the urban class level, namely aggregating their values across all the urban patches of the landscape. Pixels that correspond to land unavailable for development, such as water bodies, have been excluded from the computation of the metrics.

**Modes of urban growth**

In addition to the conventional landscape metrics, which are computed over a single snapshot of a landscape, Liu et al. (2010) proposed a quantitative method to classify the types of urban growth occurring between two time points. To that end, for each new urban patch, the Landscape Expansion Index (LEI) is computed as:

\[
\text{LEI} = \frac{L_c}{P}
\]

where \(L_c\) denotes the length of the interface between the new urban patch and pre-existing urban patches, and \(P\) is the perimeter of the new urban patch. Then, the type urban growth attributed to a new urban patch will be identified as infilling when \(\text{LEI} > 0.5\), edge-expansion when \(0 < \text{LEI} \leq 0.5\) and leapfrog when \(\text{LEI} = 0\).

**Results**

**Area–radius relationship**

The area–radius relationship of the three urban agglomerations at each temporal snapshot is plotted in Fig. 3.

On the one hand, the urban agglomerations of Bern and Lausanne show an area–radius relationship that is significantly better approximated by two line segments in a log–log scale (as suggested by the R² values of the ordinary linear regression and the piecewise regression with two line segments respectively, see Code S1), hence consistent with the bifractal city model suggested by White and Engelen (1993). In the two urban agglomerations, the breakpoints that separate the inner and outer zones are located around a 3 km distance of the city center and remain very stable through time in the case of Bern, while a slight tendency to increase might be noted in Lausanne, from 2.7 km in 1980 to 3.3 km in 2014. On the other hand, area–radius relationship of Zurich is significantly steeper than its counterparts. Considering the R² of the simple and the piecewise regressions, such relationship might also be approximated by a single straight line in the log–log scale (see Code S1). Nonetheless, the two-segment fit for Zurich yields a breakpoint that is initially located at 5.2 km from the city center in 1982 and increases to 6.7 km in 2016.

Overall, the results suggests that Zurich fills a higher proportion of the available space, especially at large radial distances from the agglomeration center. At the same time, the area–radius relationship becomes steeper through time in the three urban agglomerations—a trend that is more notable in the outer zones. This suggests that as the two agglomerations become more urbanized, their area–radius relationship could tend towards the almost straight line in the log–log scale observed in Zurich (see Code S1).

**Time series of landscape metrics**

The computed time series of landscape metrics for Bern, Lausanne and Zurich at the extents of the whole agglomeration, the inner zone and outer zone are displayed in Fig. 4 (see Code S2).
The proportion of landscape occupied by urban patches has increased monotonically for the three agglomerations and at the three extents. At the agglomeration extent, Bern and Lausanne show almost indistinguishable trends, starting from a 13% in the early 1980s and surpass the 16% in the last snapshot of 2013 and 2014 respectively, while Zurich shows a parallel trend with the percentage of urbanized land increasing from 22% in 1982 to a 27% in 2016. The inner zones of Bern and Lausanne are strongly urbanized, with the proportion of urbanized landscape showing a steady increase and surpassing the 70% and 80% respectively, whereas the inner zone of Zurich shows a smaller proportion of urbanized land, gradually increasing from a 54% in 1982 to a 58% in 2016. In the outer zone, Bern and Lausanne show a limited degree of urbanization, increasing from an initial 11% to 14% and 16% respectively, while in the outer zone of Zurich, the proportion of urbanized landscape is initially at almost 20% and surpasses the 25% in the last survey period. The number of urban patches per area unit, namely the patch density, shows the most irregular pattern. At the agglomeration extent and in the outer zone, none of the urban areas exhibit a discernable trend. In the inner zone, an overall decrease is observed in the three urban areas, nonetheless, such a trend is only monotonic in Zurich. On the other hand, the density of edges between urban and natural patches displays at the three extents similar trends for Bern and Lausanne, which differ significantly from those observed in Zurich. Bern and Lausanne show a monotonic increase at the agglomeration extent as well as in the outer zone, which contrasts with the monotonic decrease exhibited by Zurich. In contrast, the three urban

| Metric name                               | Category          | Description                                                                 |
|-------------------------------------------|-------------------|-----------------------------------------------------------------------------|
| Percentage of landscape (PLAND)           | Area and edge     | Percentage of landscape, in terms of area, occupied by patches of a given class |
| Patch density (PD)                        | Aggregation       | The number of patches per area unit                                          |
| Edge density (ED)                         | Area and edge     | Sum of the lengths of all edge segments per area unit                        |
| Area-weighted mean fractal dimension (AWMFD) | Shape            | Mean patch fractal dimension weighted by relative patch area                |
| Mean euclidean nearest neighbor distance (ENN) | Aggregation   | Mean patch shortest edge-to-edge distance to the nearest neighboring patch of the same or different class |

A more thorough description can be found in the documentation of the software FRAGSTATS v4 (McGarigal et al. 2012)

The proportion of landscape occupied by urban patches has increased monotonically for the three agglomerations and at the three extents. At the agglomeration extent, Bern and Lausanne show almost indistinguishable trends, starting from a 13% in the early 1980s and surpass the 16% in the last snapshot of 2013 and 2014 respectively, while Zurich shows a parallel trend with the percentage of urbanized land increasing from 22% in 1982 to a 27% in 2016. The inner zones of Bern and Lausanne are strongly urbanized, with the proportion of urbanized landscape showing a steady increase and surpassing the 70% and 80% respectively, whereas the inner zone of Zurich shows a smaller proportion of urbanized land, gradually increasing from a 54% in 1982 to a 58% in 2016. In the outer zone, Bern and Lausanne show a limited degree of urbanization, increasing from an initial 11% to 14% and 16% respectively, while in the outer zone of Zurich, the proportion of urbanized landscape is initially at almost 20% and surpasses the 25% in the last survey period. The number of urban patches per area unit, namely the patch density, shows the most irregular pattern. At the agglomeration extent and in the outer zone, none of the urban areas exhibit a discernable trend. In the inner zone, an overall decrease is observed in the three urban areas, nonetheless, such a trend is only monotonic in Zurich. On the other hand, the density of edges between urban and natural patches displays at the three extents similar trends for Bern and Lausanne, which differ significantly from those observed in Zurich. Bern and Lausanne show a monotonic increase at the agglomeration extent as well as in the outer zone, which contrasts with the monotonic decrease exhibited by Zurich. In contrast, the three urban

![Fig. 3](https://www.openstreetmap.org/). The upper inset shows the evolution along the temporal snapshots of the breakpoint \( r_0 \) (in m) for the two-segment regression that minimizes the sum of squared residuals, while the lower inset shows the evolution along the temporal snapshots of the coefficient of determination \( R^2 \) of the single-segment fit (blue) and of the two-segment piecewise fit (orange). See Code S1

Table 1

| Metric name                               | Category          | Description                                                                 |
|-------------------------------------------|-------------------|-----------------------------------------------------------------------------|
| Percentage of landscape (PLAND)           | Area and edge     | Percentage of landscape, in terms of area, occupied by patches of a given class |
| Patch density (PD)                        | Aggregation       | The number of patches per area unit                                          |
| Edge density (ED)                         | Area and edge     | Sum of the lengths of all edge segments per area unit                        |
| Area-weighted mean fractal dimension (AWMFD) | Shape            | Mean patch fractal dimension weighted by relative patch area                |
| Mean euclidean nearest neighbor distance (ENN) | Aggregation   | Mean patch shortest edge-to-edge distance to the nearest neighboring patch of the same or different class |
agglomerations show a clear decrease in the inner zone, which is more notable in Lausanne.

Regarding the shape complexity of urban patches, represented by the area-weighted mean fractal dimension, the three urban agglomerations show distinctive patterns. In Bern, an overall increase might be noted at the agglomeration extent and in the outer zone, in both cases with a slight decline in the latter period which is reminiscent of an unimodal pattern. In Lausanne, a clearer unimodal pattern is observed also at the agglomeration and outer zone extents. At the inner zone, the three urban agglomerations display a monotonic decrease, which likewise for the edge density, is most pronounced in Lausanne.

---

Fig. 4 Time series of landscape metrics, computed at the urban class level
Finally, the distance between urban patches, reflected by the mean euclidean-nearest neighbor metric, shows an overall decrease at the agglomeration extent for Bern and Lausanne, while an unimodal pattern is observed in Zurich. The latter suggests that urban patches in the Zurich agglomeration became more distant between the first and second temporal snapshots and became more connected throughout the third and fourth temporal snapshots. In the inner zone, a monotonic decrease is observed in Lausanne whereas Bern and Zurich do not exhibit any discernible trend. In the outer zone, the three urban agglomerations show a monotonic decrease, suggesting that at that extent, urban patches are becoming more connected on average.

Growth modes

The changes in the relative dominance of the three growth modes, namely infilling, edge expansion and leapfrog, are displayed in Fig. 5 (see Code S3). The relative dominance of the three growth modes shows almost indistinguishable trends at the agglomeration extent and in the outer zone, while a completely different pattern is observed in the inner zone. As with the time series of several landscape metrics, similar patterns might be noted in Bern and Lausanne. At the agglomeration extent and in the outer zone, edge-expansion is the most dominant mode of growth in the two urban areas, although its influence decreases throughout the period of study from a 62% to a 53% in Bern and from a 58% to a 55% in Lausanne (at the agglomeration extent). Such decrease is mostly at the expense of an increase on the relative dominance of infilling, which grows from 26 to 32% in Bern and from 30 to 35% (at the agglomeration extent). A similar trend is observed at the agglomeration extent and outer zone of Zurich, yet in this case the dominance of infilling surpasses that of edge expansion in the last period (47% of infilling versus a 44% of edge expansion at the agglomeration extent). Lastly, at the agglomeration extent and in the outer zone, leapfrog is by far the least dominant growth mode albeit there is no observable diminishment of its influence.

The inner zones of Bern and Lausanne are clearly dominated by infilling, with the evolution of its influence exhibiting a slight decline in Bern from 81 to 77% that contrasts with the noticeable increment from 61 to 90% observed in Lausanne. In the inner zone of Zurich, infilling is also the most dominant growth mode with a dominance that remains between 60% and 70% without a discernable trend. Additionally, the influence of edge expansion in the inner zone of Zurich, i.e., 35% in the last period, is significantly above its counterparts in Bern and Lausanne, i.e., 23% and 10% respectively in the last period. Lastly, in the three urban agglomerations, the influence leapfrog is practically irrelevant in the inner zone.

Discussion

Testing hypothesis of urbanization patterns

The results of this study can be used to explore whether there exist generalities and regularities in the spatiotemporal patterns of urbanization. In this respect, a central question is to what extent the observed transformation of the landscapes conform to the prominent models of urbanization defined by the diffusion and coalescence hypothesis and the three growth mode hypothesis.

The idea of urban growth as a two-phase alternating process of diffusion and coalescence was formulated by Dietzel et al. (2005) as a testable temporal pattern of landscape metrics: during the diffusion stage, the patch density, edge density, area-weighted mean fractal dimension and mean euclidean nearest-neighbor distance of urban patches should increase at first, reach an apex at different times and then decrease as patches start to coalesce, showing an overall unimodal pattern. The time series of landscape metrics of this study show mixed support for the diffusion and coalescence hypothesis. At the agglomeration extent, the trends of the edge density and the area-weighted mean fractal dimension, which reflect the structural complexity of the landscape, suggest that Zurich is already at the coalescence stage, whereas Bern and Lausanne are seemingly undergoing a transition between diffusion and coalescence. Nevertheless, the irregular pattern exhibited by the density of urban patches is in strong dissonance with the unimodal pattern supposed by the diffusion and coalescence model. Examining the time series of landscape metrics in the inner and outer zones provides additional insights that enlighten the peculiarities of the undergoing urbanization patterns. In Bern, the decreases of
the patch density, edge density and area-weighted mean fractal dimension in the inner zone suggest that such extent is undergoing a coalescence process which contrasts with the pattern observed in the outer zone, where the increases of the edge density and area-weighted mean fractal dimension are characteristic of the diffusion stage. A similar pattern might be noted in Lausanne, however, the area-weighted mean fractal dimension at the outer extent does not show an increase but rather an unimodal pattern, which reflects that the shape complexity of urban patches in the outer zone has reached an apex after the first period and then progressively started to decline. This suggests that the inner zone of Lausanne is undergoing a coalescence process while the outer zone is seemingly at the transition between diffusion and coalescence. Finally, with the modest exception of the increase in the last period of the patch density in the agglomeration and outer extents of Zurich, the three metrics show monotonic decreases at the three considered extents, which indicates that both the inner and outer zone of Zurich show the characteristics of the coalescence stages.

The irregular trend of the patch density observed in the three urban agglomerations is evidence that new urban patches might emerge at any period. Such a remark is reminiscent of the critique to the diffusion and coalescence model by Li et al. (2013), who suggested that such dichotomy can be misleadingly over-simplistic because, in reality, the three growth modes of infilling, edge-expansion and leapfrog operate simultaneously, and thus “it is more plausible to view urbanization as a spiraling process that involves three growth modes of leapfrogging, edge-expanding and infilling [where] leapfrog and infilling tend to alternate in their relative dominance while edge-expansion is likely to remain its importance throughout much of the urbanization process” (pp. 1885–1886). The results of this study are primarily consistent with such model, nevertheless, a thorough examination allows for further clarifications. On the one hand, at the agglomeration extent, the
importance of leapfrog growth does not necessarily decrease over time, instead it seems that infilling is becoming increasingly influential at the expense of edge-expansion. On the other hand, the influence of the three growth modes changes dramatically when inspecting the results in the inner zone, which is mostly dominated by infilling, and the presence of leapfrog growth is either completely inexistent or practically insignificant. This challenges the overall validity of the three growth modes hypothesis, especially since the alleged simultaneous action of the three growth modes does not hold for the inner zone extent. Overall, the results of this study suggest that both the diffusion and coalescence as well as the three growth modes models of urbanization should be extended by clarifying the patterns that are to be expected at each extent—and that such extent should be systematically defined according to quantitative criteria, as for example, the breakpoint location in the area–radius relationship.

Identifying characteristic extents in urban agglomerations

In the present study, a fractal analysis of the area–radius relationship has been exploited to define the extents at which the landscape metrics and growth modes have been computed. More precisely, the employed approach is based on the bifractal city model suggested by White and Engelen (1993), which is characterized by the existence of a kink in the area–radius relationship that separates an urban agglomeration into an inner zone where urbanization is essentially complete, and an outer zone that is still undergoing active development of natural land into urban uses. Although the existence of such a kink is also noted in the extensive fractal analysis of a number of cities around the world by Frankhauser (1994), the bifractal city model lacks an established method to validate it quantitatively. In consonance with the area–radius plots, comparing the coefficients of adjustments of the simple and piecewise regressions suggests that Bern and Lausanne can be significantly better approximated by two curves. However, it is trivial to show that increasing the number of segments in such a piecewise regression will always lead to a greater or equal coefficient of adjustment. In this study, the bifractal model has been assumed by exogenously fixing the number of segments to two before the piecewise regression, yet further deliberation is required in order to develop methods to properly identify distinct scaling regimes in urban area–radius curves.

Another issue of concern arises from the assumption of a monocentric organization that underlies the bifractal city model. While such assumption is statistically confirmed in the three urban agglomerations by the way in which the slope of the area–radius relationship decreases with increasing radius, this might be largely attributable to how the extents of the urban agglomerations adopted in this study have been constructed, i.e., based on functional criteria such as employment and commuting behavior (SFSO 2014). Furthermore, the boundaries between neighboring urban agglomerations in the Swiss Plateau are starting to permeate—for instance, the urban agglomerations of Lausanne and its neighboring Vevey–Montreux practically configure an urban continuum, and the same might be noted for the urban agglomerations of Zurich and Baden–Brugg. Therefore, it might be appropriate to employ other quantitative approaches to detect urban agglomeration boundaries based on land use/land cover characteristics, such as those based on percolation theory (Rozenfeld et al. 2008) or fractal analysis (Tannier and Thomas 2013), which would likely yield more polycentric patterns.

Conclusion

The present study combines three different approaches to study the spatiotemporal patterns of land use change associated to urbanization in three of the main Swiss urban agglomerations over four surveys in the period from 1980 to 2016. Fractal analysis of the area–radius relationship of urban land is employed to separate the urban agglomeration into two characteristic extents, the inner and outer zones, in which the landscape metrics and the growth modes are computed. The results show that the three urban agglomerations can show very distinct spatiotemporal patterns in the inner and outer zones. On the one hand, Bern and Lausanne present most characteristics of the coalescence stage in the inner zone, whereas the outer zone displays many traits of the diffusion stage. On the other hand, leapfrog growth is practically nonexistent in the inner zone, which is mainly dominated by infilling. Therefore, spatiotemporal hypotheses of urban land use
change should be revised to consider the way in which contemporary cities are configured by a different characteristic extents where urbanization exhibits distinct spatial signatures.

Supplementary Material

Code S1

Exploration of the area–radius scaling of each urban agglomerations over the whole period of study, as Jupyter Notebook (IPYNB). https://github.com/martibosch/swiss-urbanization/blob/published/notebooks/area_radius_scaling.ipynb.

Code S2

Computation of the time series of landscape metrics and exploration of their correlations over all the urban agglomerations and the whole period of study, as Jupyter Notebook (IPYNB). https://github.com/martibosch/swiss-urbanization/blob/published/notebooks/metrics_time_series.ipynb.

Code S3

Computation of the relative dominance of the three growth modes over all the urban agglomerations and the whole period of study, as Jupyter Notebook (IPYNB). https://github.com/martibosch/swiss-urbanization/blob/published/notebooks/growth_modes.ipynb.

Acknowledgements

This research has been supported by the École Polytechnique Fédérale de Lausanne (EPFL).

References

Alberti M (2005) The effects of urban patterns on ecosystem function. Int Reg Sci Rev 28(2):168–192
Angel S, Sheppard S, Civco DL, Buckley R, Chabaeva A, Gitlin L, Kraley A, Parent J, Perlin M (2005) The dynamics of global urban expansion. Citeseeer
Batty M (2005) Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals. MIT Press, Cambridge
Batty M (2008) The size, scale, and shape of cities. Science 319(5864):769–771
Batty M, Longley P (1994) Fractal cities: a geometry of form and function. Academic Press, San Diego
Bosch M (2019a) Pylandstats: an open-source pythonic library to compute landscape metrics. PLoS ONE 14(12):e0225734
Bosch M (2019b) swisslandstats-geopy: Python tools for preprocessing geodata from the swiss federal statistical office. J Open Source Softw 4(40):1511
Dietzel C, Herold M, Hemphill JJ, Clarke KC (2005) Spatiotemporal dynamics in California’s central valley: empirical links to urban theory. Int J Geogr Inf Sci 19(2):175–195
Frankhauser P (1994) La fractalité des structures urbaines. Anthropos, Paris
Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, Briggs JM (2008) Global change and the ecology of cities. Science 319(5864):756–760
Jaeger JA, Schwick C (2014) Improving the measurement of urban sprawl: weighted urban proliferation (WUP) and its application to Switzerland. Ecol Ind 38:294–308
Jenerette GD, Potere D (2010) Global analysis and simulation of land-use change associated with urbanization. Landsc Ecol 25(5):657–670
Li C, Li J, Wu J (2013) Quantifying the speed, growth modes, and landscape pattern changes of urbanization: a hierarchical patch dynamics approach. Landsc Ecol 28(10):1875–1888
Liu Z, He C, Wu J (2016) General spatiotemporal patterns of urbanization: an examination of 16 world cities. Sustainability 8(1):41
Liu X, Li X, Chen Y, Tan Z, Li S, Ai B (2010) A new landscape index for quantifying urban expansion using multi-temporal remotely sensed data. Landsc Ecol 25(5):671–682
Mandelbrot BB (1983) The fractal geometry of nature, vol 173. W.H. Freeman, New York
McGarigal K, Cushman SA, Ene E (2012) Fragstats v4: spatial pattern analysis program for categorical and continuous maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. http://www.umass.edu/landeco/research/fragstats/fragstats.html. Accessed 5 Mar 2020
Nong DH, Lepczyk CA, Miura T, Fox JM (2018) Quantifying urban growth patterns in hanoi using landscape expansion modes and time series spatial metrics. PLoS ONE 13(5):e0196940
Price B, Kienast F, Seidl I, Ginzler C, Verburg PH, Bolliger J (2015) Future landscapes of switzerland: risk areas for urbanisation and land abandonment. Appl Geogr 57:32–41
Riitters KH, O’Neill R, Hunsaker C, Wickham JD, Yankee D, Timmins S, Jones K, Jackson B (1995) A factor analysis of landscape pattern and structure metrics. Landsc Ecol 10(1):23–39
Rozenfeld HD, Rybski D, Andrade JS, Batty M, Stanley HE, Makse HA (2008) Laws of population growth. Proc Natl Acad Sci 105(48):18702–18707
Schneider A, Woodcock CE (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 Stud 45(3):659–692
Seto KC, Fragkias M (2005) Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. Landsc Ecol 20(7):871–888

Storn R, Price K (1997) Differential evolution—a simple and efficient heuristic for global optimization over continuous spaces. J Glob Optim 11(4):341–359

Swiss Federal Statistical Office (2014) L’espace à caractère urbain en Suisse en 2012: Une nouvelle définition des agglomérations et d’autres catégories d’espace urbain. https://www.bfs.admin.ch/bfs/fr/home/statistiques/themes-transversaux/analyses-spatiales/niveaux-geographiques.assetdetail.349554.html. Accessed 17 Apr 2019

Swiss Federal Statistical Office (2017) Statistique de la superficie selon nomenclature 2004—standard. https://www.bfs.admin.ch/bfs/fr/home/services/geostat/geodonnees-statistique-federale/sol-utilisation-couverture/statistique-suisse-superficie/nomenclature-standard.assetdetail.4103540.html (in French). Accessed 18 Apr 2019

Swiss Federal Statistical Office (2018) City statistics (urban audit). Data collection. https://www.bfs.admin.ch/bfs/en/home/statistics/cross-sectional-topics/city-statistics.html. Accessed 16 Apr 2019

Tannier C, Thomas I (2013) Defining and characterizing urban boundaries: a fractal analysis of theoretical cities and Belgian cities. Comput Environ Urban Syst 41:234–248

White R, Engelen G (1993) Cellular automata and fractal urban form: a cellular modelling approach to the evolution of urban land-use patterns. Environ Plan A 25(8):1175–1199

White R, Engelen G, Uljee I (2015) Modeling cities and regions as complex systems: from theory to planning applications. MIT Press, Cambridge

Wu J (2004) Effects of changing scale on landscape pattern analysis: scaling relations. Landsc Ecol 19(2):125–138

Wu J (2014) Urban ecology and sustainability: the state-of-the-science and future directions. Landsc Urban Plan 125:209–221

Wu J, Jenerette GD, Buyantuyev A, Redman CL (2011) Quantifying spatiotemporal patterns of urbanization: the case of the two fastest growing metropolitan regions in the United States. Ecol Complex 8(1):1–8

Wu J, Shen W, Sun W, Tueller PT (2002) Empirical patterns of the effects of changing scale on landscape metrics. Landsc Ecol 17(8):761–782

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.