Types of Morphological Configurations of the City across the Globe – a Remote Sensing based Comparative Approach

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1 ABSTRACT

The spatial configuration of the built city is like DNA – it is unique to each city. And yet, it could be shown, that spatial configurations of cities are very similar in certain geographical regions on our globe and, in turn, very different from other regions. In this study, the classification scheme of local climate zones (LCZs) is applied to spatially map the morphological appearances of the cities across the globe. We empirically explore their spatial configurations using different city models and three alternative data representations. We use a single spatial unit model to compute a global land use mixture, a monocentric model to compute density diffusion, as well as to describe a concentric land use mixture at intra-urban scale. We then, for each data representation, cluster cities using k-means to extract typologies of urban morphology. While the results show 1) the geographical congruence of some types of urban morphology, they also show that there are also 2) strong intra-regional variabilities, and 3) multiple cross-regional types. These point to deeper premises than the geographical location of the respective city as main encoder for the city's DNA. Through the comparison of the results obtained for the three data representation, we discuss these various aspects.

Keywords: Urban morphological patterns, Local Climate Zones, Remote sensing, City models, Comparative urban research

2 INTRODUCTION

Cities, in their diversity, offer a large variation of physical faces. Far from representing the city as a single object spread across the globe (Park et al., 1925), urban geography quickly recognised urban structures that differ significantly from one city to another (Harris & Ullman, 1945). Despite this non-universality, one can still perceive shared patterns between specific cities, as if they were sharing family ties. Many have argued on those ties with typologies based on their social, economic or political functions (Braunfels, 1976; Harris & Ullman, 1945; Henderson, 1974). However, cross-sectional studies of the morphologies of cities tend to mitigate the explicative power of such typologies on city structure (Kostof, 1991). Instead, cultural factors seem way more explanatory in this sense (Ehlers, 1993; Gaubatz, 1998; Griffin & Ford, 1980; Hahn, 2014; Krapf-Askari, 1969; Lichtenberger, 1972). Taubenböck et al. (2020) showed that culture is a non-neglectable factor that is embedded in the physical face of cities. Nonetheless, culture in the ethnic sense as defined by Huntington (Huntington, 1998) or Kolb (Kolb, 1962) does not correlate perfectly with morphologic types of cities found in previous work. It seems logical, then, that we must redefine or at least supplement the typology presented so far. Therefore, in defining an improved morphologic city typology, we step away from the solely cultural frame, at least initially. In this sense, this paper attempts an alternative approach to the work presented in Taubenböck et al. (2020).

To extract typologies of cities from the large variety in which they exist, we apply here a purely physical approach, i.e. we focus on the built and natural elements of the urban landscape. We rely here on intra-urban morphological descriptions of their physicality through geometrical parameters, such as the built-up surface fraction, building height, or semantic classifications such as, in our case, Local Climate Zones. We consider these characterisations of the salient built-up types and their arrangement as a typology of the land use mixture.

The recent developments of remote sensing as a field and the large availability of satellite data, such as the Sentinel constellation, enable in combination with image data analysis techniques in the domain of artificial intelligence the large-scale production of richly spatial data on land cover. In our case we rely on a Local Climate Zone (LCZ) (Stewart & Oke, 2012) classification across the globe. This frame proves to be suited for large scale studies of the urban morphology. If they are aggregated in a consistent manner, they can shed light on key elements to understand the geography of the city (Bechtel et al., 2015). In order to measure spatiality and distribution within cities, there exist different spatial models such as single spatial units, monocentric, polycentric or more sophisticated models in urban geography. We understand here the single spatial unit as the straightforward approach treating the city as a single object bounded to a specific extent. The monocentric model acknowledges an inhomogeneous distribution of the properties of a city based on the distance to its centre (Park et al., 1925). The polycentric model further acknowledges this inhomogeneous character to be organised around multiple nuclei (Adolphson, 2009; Harris & Ullman, 1945; Siedentop et al., 2003).

In this study, we rely on two spatial model approaches: the single spatial unit and a monocentric model. For the global analysis based on three data representations of the intra-urban morphology, we offer a qualitative comparison between the obtained quantitative results. To do so, we rely on a LCZ land-cover classification allowing to quantify morphological categories. We propose three ways of presenting the data based on 1) geographical units considered and 2) the semantics of the data used. With it, we identify, 3) different types of cities among our global sample of 110 urban areas. With these results we try to propose a multi-parameters quantitative description of morphological typologies of cities.

3 CONCEPT, DATA AND METHODOLOGY

3.1 Conceptual foundation

The conceptual foundation of this study is based on an unsupervised classification of cities based on similar spatial configurations. The selection of cities under investigation is a balanced sample of urban areas across the globe. In those cities, we gather data following the LCZ frame. Even though this frame was originally developed as a tool relating to the urban climate, the classification scheme relies on a morphological description of the built and natural urban landscape. This source of data provides rich information on the intra-urban morphology (Bechtel et al., 2015), which is our object of analysis. As for being consistent in terms of spatial units, we use the Morphological Urban Areas (MUAs) (Taubenböck et al., 2019), a delimitation of cities based on a data-driven approach instead of administrative units which are artificial spatial units and thus less appropriate for geographic comparisons. For each city we extract from the LCZ classification three representations of their spatial configuration. The three data representations are namely a ‘global model of land use mixture’, a ‘concentric model of built-up density’, and a ‘concentric model of land use mixture’. For each model, we apply an unsupervised classification approach. Thus, we aim to identify morphological city types that are similar in their spatial expression.

3.2 Data

3.2.1 Study site selection

We base our selection of the study sites on demographic statistics from the United Nations (UN, 2018). We limit our study to 110 cities. We ensure the balance of representativity between continents by the following conditions: first we compute the relative share of urban population by continent. Within each continent, we select a respective sample of cities whose cumulative population corresponds to the share of the continent. However, such a selection cannot be perfectly fitting each share. Thus, we allow a tolerance error of 3% and keep the set of cities that enable us to stay within this margin. Beyond, we primarily select cities with large populations and ensure that there is a certain spatial coverage within the continent.

3.2.2 LCZ frame

The LCZ frame was first developed in Oke & Canada, (2006) to study urban climate. The unique scheme proposes nonetheless valuable data on intra-urban morphology. Stewart and Oke (Stewart & Oke, 2012) defined 17 thematic LCZs split into built types (LCZs types 1-10) and non-built types (LCZs types A-G). These types are defined through standardised measurable morphological parameters such as ‘density’, 'building size', 'building -or tree height' and 'open spaces'. Therefore these "regions of uniform surface cover, structure, material, and human activity span hundreds of meters to several kilometres in horizontal scale" (Stewart & Oke, 2012). They depict a range of built and non-built urban types in a universal, culturally-neutral manner, suiting the purpose of our study. The LCZ frame allows to consider the morphological configuration of a city embedded in this spatialised description of land-use mixture.

3.2.3 LCZ classification

As a consistent source we rely on a classification of LCZs produced by (Qiu et al., 2019). This work uses a recurrent residual network on multi-seasonal Sentinel-2 multi-spectral optical imagery of 10 to 60m resolution. The Re-ResNet was trained on the LCZ42 dataset. This dataset was produced on 42 cities across the globe by 15 domain experts and an overall confidence of 85% was assessed (Zhu et al., 2019). The final product is a 100m resolution LCZ classification covering our sample of 110 cities.

3.2.4 Spatial Units

For an admissible, geographical comparison, it is essential to relate the objects of comparison (here cities) to comparable spatial units. Thus, we argue here not to rely on administrative boundaries as they vary greatly in their definition between regions of the world and therefore are questionable in their consistency. We therefore use the MUAs provided by Taubenböck et al. (2019), i.e. a data-driven, consistent delineation between urban and rural realms.

3.3 Methodology

3.3.1 Descriptions of the configuration of cities

The LCZ classifications offer for each city a spatialised description of its land-use mixture. To produce a systematic analysis of this mixture, we reduce the dimensionality of the data. Therefore, we propose three models of representation of the LCZ classification:

First, we propose a 'global land-use mixture model' to depict the general land use characteristics of cities. For this model, we compute the share of each of the 17 types of LCZs within the boundaries of the MUAs. As an additional feature, we take the size of the MUA into account. With it, this model contains an 18-dimensional feature space.

Second, we apply a 'concentric model of density'. With it, we examine the dispersion of the built-up density in relation to the defined urban centre. To do so, we derive the built-up density as a derivation of the LCZ thematic classes. We retrieve the share of built-up fraction and the roughness element (height) from the semantic types of the LCZ classes. By multiplication of the built-up fraction and the roughness element, we approximate the built-up volume as a proxy of 3-dimensional (3-d) built-up density. For the spatiality of the monocentric model, we define 100 rings of width proportional to the maximum radius of the MUAs. For each of the concentric rings, we compute the average 3-d built-up density. By considering the concentric rings of MUAs here, we then obtain a 101-dimentional feature space that describes the concentric evolution of 3-d built-up density.

Third and last, we apply again a 'concentric model of the land-use mixture' that allows conclusions about the morphological configuration of the mixed urban structure as a function of distance from the MUA centre. To do so, we compute, in the same manner as above 100 concentric rings covering the MUAs. Within each ring, the share of each of the 17 LCZ classes is computed. For the final feature space, the size of the MUA is additionally integrated. Overall, this approach results in a 1701-dimentional feature space.

3.3.2 Clustering of cities

We consider our 18-, 101- and 1701-dimentional feature spaces as the descriptors of the morphological configuration of the cities studied. Based on these three feature spaces, we investigate the possible similarities and dissimilarities between the spatial configurations of cities. By an unsupervised clustering method, namely the k-means (Hartigan & Wong, 1979), we aim at a statistical grouping of cities. In this approach, a specific number of clusters is not pre-defined. Therefore, we determine for each of the models the optimal number of separable clusters relying on the gap statistic method (Tibshirani et al., 2001).

ISBN 978-3-9504945-0-1. Editors: M. SCHRENK, V. V: POPOVICH, P. ZEILE, P. ELISEI, C.BEYER, J. RYSER, G. STÖGLEHNER

3.3.3 Description of the typologies

For each of the models, we visually represent our clustering results on a map. The different clusters will be represented by different colours. It must be mentioned that the clustering is not consistent across the three models. Therefore, the colours representing the clusters are chosen arbitrarily. We chose to use the same set of colours between the three results to highlight the similarities between the three approaches, but we point out that the clusters found across the models are not the same.

Subsequently we describe the morphology of the three typologies obtained with both textual and visual support. Visually we propose for each typology a figure of three parts: 1) A comparison, between clusters, of the LCZ shares. This is composed of 17 sub-figures, one for each LCZ class. The LCZ is indicated by the title of the sub-figure and the colour of the frame. For the specific LCZ are plotted the distributions of the share (in %), in the shape of a boxplot, of each cluster, side by side. The clusters are indicated by the colour of the boxplot. 2) A concentric repartition of the shares of LCZ classes. Each of the nested pie charts represents the averaged results of the cities of one cluster. The colour of the cluster is indicated by the title of the nested pie chart and the colour circling it. The nested pie charts are made of 5 concentric zones. Each of the zone is accounting for a fifth of the extent of the averaged city of the cluster. The zone is then to be read as a pie chart, the share of each LCZ class is depicted by its proportion on the chart. 3) An averaged profile of the built-up volume in relation to the distance to the centre of each cluster, indicated by its colour.

We then draw upon these descriptions to compare the results obtained through the three different models.

4 RESULTS

4.1 Geographical distribution of the clusters

In general, we find that there are definitely, regardless of feature spaces, groups of cities that have similar morphological configurations. Some lie, as one possible influencing factor, within a cultural or geographic region. However, the various morphological compositions are complex and fuzzy within and across regions. Our results also show that the feature space has a decisive influence on the obtained results. The identified clusters vary and it can be seen that spatial statistics are prone to ambiguities. As an example, we refer to the European continent (Fig. 1): in the 18-dimensional and 1701-dimensional feature space, the unsupervised classification groups most of the European cities into one cluster. In the 101-dimensional feature space, however, this is not the case. More detailed descriptions can be found below.

4.2 Morphological descriptions of the clusters

4.2.1 Typology of the ‘global model of land use mixture’

In the global model of land use mixture, the red cluster is located mostly in North- and South-America and in East Asia. It is defined by a relatively high share of large low-rise buildings (LCZ-8) and dense trees (LCZ-A) as well as, comparatively to the other clusters, low share of low plants (LCZ-D). The presence of the large low-rise buildings is consistent through the city but the share of dense trees, as well as the rest of the non-built-up land, from almost none in the core, augment progressively toward the periphery. The cities are large with an average radius of 25.1km. We observe a rather dense profile on average with a decrease in bulges, probably indicating secondary local centres of density.

Cities of the orange cluster can be found on the western coastline of the Pacific and on the U.S. west coast. They are relatively average in terms of LCZ shares. Exceptions are a slightly higher presence of water (LCZ-G) and a high share of large low-rise buildings (LCZ-8). This presence is consistent through the five concentric zones and gains a slight increase in the outermost one. The share of the vegetation is at maximum in the fourth zone. This, with the multiple bulges of the volume profile points to multiple-nuclei metropolis, with 37.4km in average -being the largest among clusters.

The yellow cluster is located mostly in East Africa, East and Central Asia. It is characterised by its high shares of open low-rise buildings (LCZ-6), sparsely built-up areas (LCZ-9) and scattered trees (LCZ-B). These LCZ classes become more and more prevalent toward the outskirts of the cities. This defines a slowly decreasing profile of built-up volume for these relatively small cities (12.2km of radius in average).

Most of the cities of the green cluster are located in Northern Africa and Western Asia. The cluster is defined by a high share of bare soil or sand (LCZ-F) and the presence of only low vegetation types. Despite the large dominance of non-built land in the outskirts, the cities are of average size with 15.2km depicted by a profile rapidly decreasing and then stabilising almost on a plateau of low built-up volume.

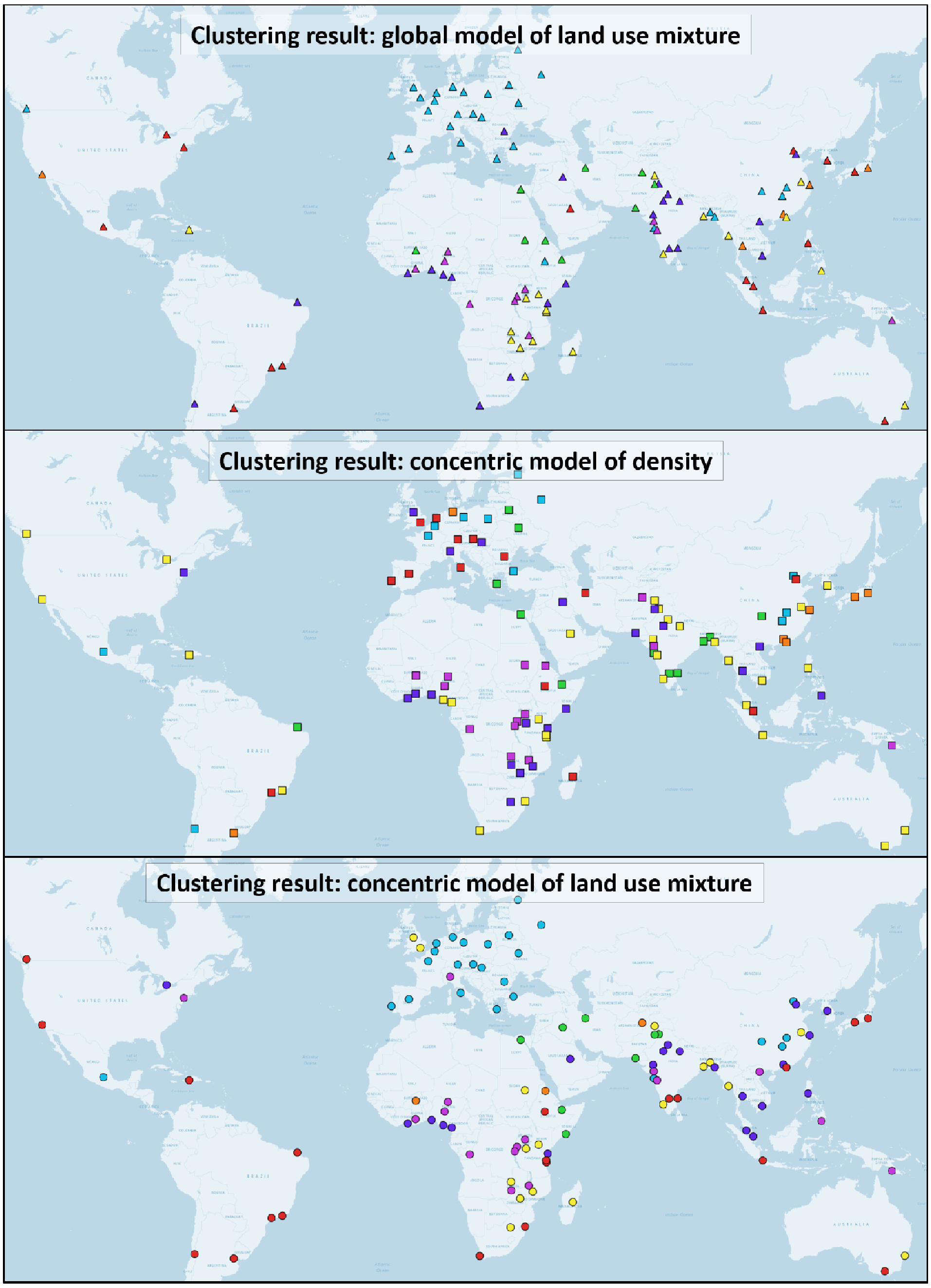

Figure 1:Maps of the results of the clustering for the global model of land use mixture (top); concentric model of density (middle); concentric model of land use mixture (bottom)

Most of the cities of the blue cluster are located in Europe. This cluster is characterised by the high share of open midrise structures (LCZ-5) as well as compact midrise (LCZ-2) and open high-rise buildings (LCZ-4). Concentrated in the core of the cities, these LCZ classes give way toward the periphery to more vegetation and large low-rise buildings (LCZ-8). The built-up volume decreases in a concave shape along the 13.7km of average radius.

The cities of the indigo cluster of this typology are mostly spread across the shores of sub-Saharan Africa, India, South America and South-East Asia. They have a comparatively higher share of lightweight low-rise buildings (LCZ-7), a quite large portion of large low-rise buildings (LCZ-8) and a fair amount of low plants (LCZ-D). The latter is predominantly present in the fifth concentric zone, where it accounts for almost half of the land. The built-up volume decreases in a slow concave manner for, on average, 14.9km. The details of the statistical analysis are illustrated in Fig. 2.

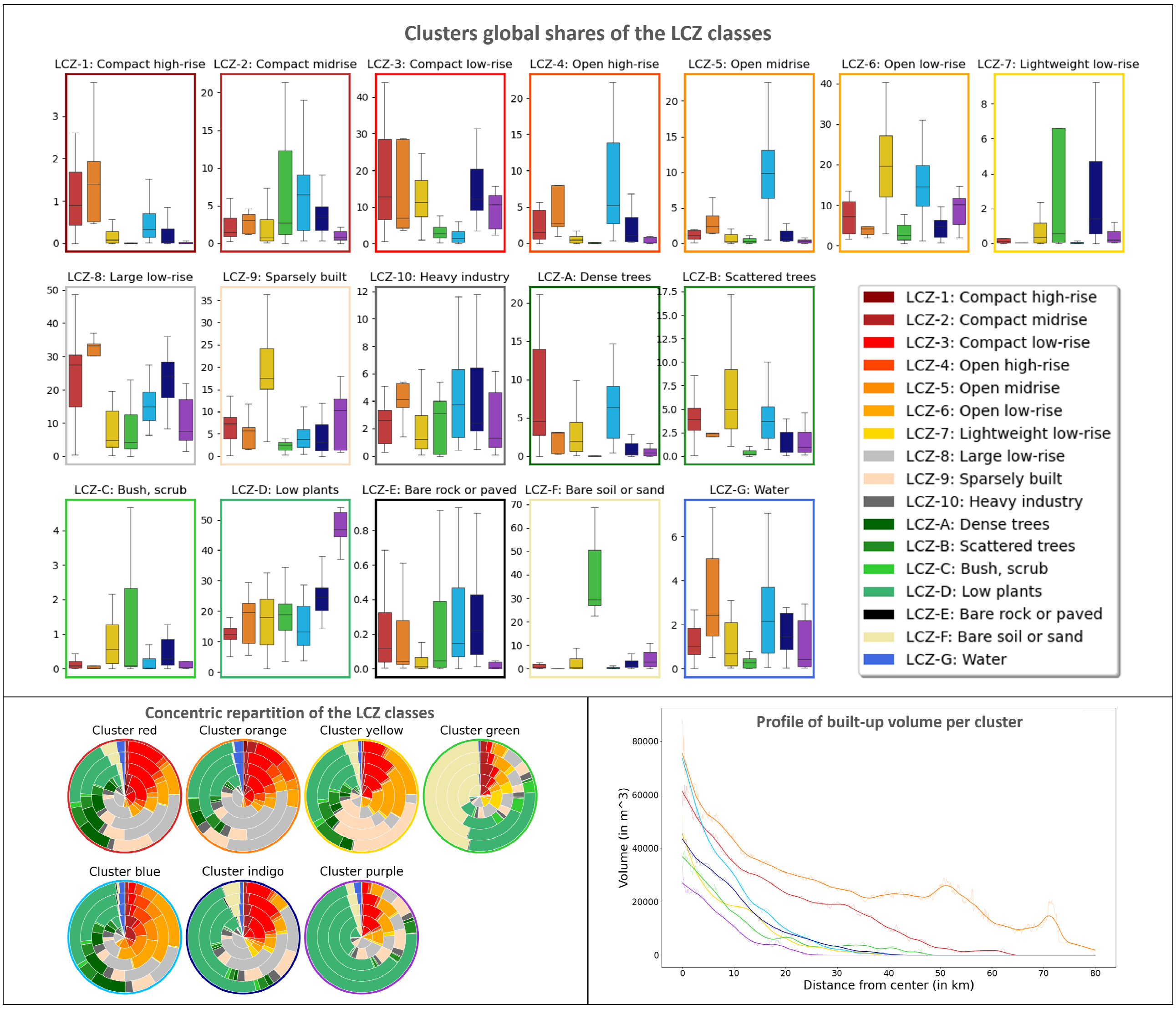

Figure 2: Morphological description of the clusters obtained for the global model of land use mixture

Last, the purple cluster is located mostly in inland sub-Saharan Africa and western India. This cluster is remarkable for its overall low share of built-up lands and the highest presence of low plants (LCZ-D) among the clusters. This class, already present in the inner part of the concentric zones, is almost covering three quarters of the fifth zone. This results in the lowest profile of built-up volume and the smallest cities (11.8km).

4.2.2 Typology of the concentric model of density

Cluster red is mostly located in Central and Southern Europe. It features mostly average shares in terms of LCZ shares with slightly high shares of compact midrise (LCZ-2), open midrise (LCZ-5) and scattered trees (LCZ-B). Overall it has a high share of built-up land, mainly in its core and presents a high built-up volume plummeting rapidly along its 16.6km of average radius.

The orange cluster consists of Eastern and Far-Eastern Asian harbour cities. Its cities are distinguishable by the higher presence of compact high-rise (LCZ-1), compact low-rise (LCZ-3), large low-rise buildings (LCZ-8), heavy industry (LCZ-10) and water (LCZ-G). The share of non-built-up land is low, except for the fourth of the five concentric zones, benefiting to a dense profile of built-up volume, decreasing with bulges. This seems to indicate large (28.4km) multi-nuclei metropolis.

The yellow cluster is scattered evenly across the globe, except for Europe. It is a quite average cluster in terms of LCZ shares. The spatial repartition of the LCZ classes, however, shows a large proportion of open low-rise (LCZ-6) and sparsely built structures (LCZ-9). Their share is increasing toward the peripherical zones. This low built-up volume with persistently built-up structures in the periphery produces a slowly decreasing profile running all along the average of 18.8km of those cities. The details of the statistical analysis are illustrated in Fig. 3.

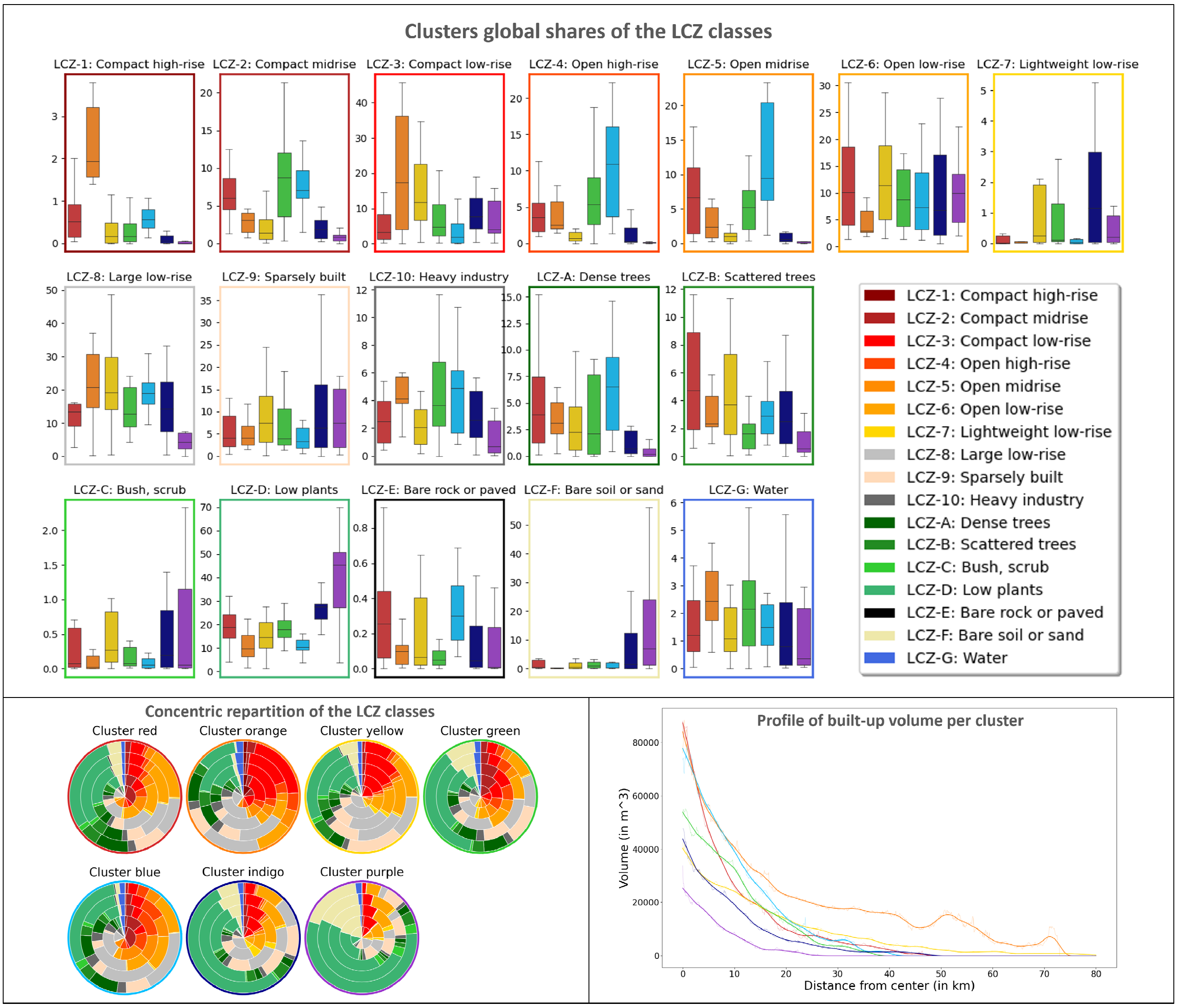

Figure 3:Morphological description of the clusters obtained for the concentric model of density

Cities of the green cluster can be found in the Indian region and in Eastern Europe. They show comparatively high proportions of compact midrise buildings (LCZ-2). Overall the group has a balanced share of the different types of built-up land. They feature a steady, almost linear decrease in its built-up volume. The cities are of average size (14.4km).

Cities of the blue cluster are mostly located in Central and Eastern Europe as well as in China. They are distinguishable by their comparatively large proportion of open high-rise (LCZ-4) and open midrise buildings (LCZ-5), as well as with heavy industries (LCZ-10) and dense trees (LCZ-A). They feature a core with a high share of the dense built-up classes, leaving progressively place to large low-rise buildings (LCZ-8). This is depicted by a high central built-up volume decreasing linearly with the distance to the centre. The cities of this cluster are on average of 17.2km of radius.

The indigo cluster is dispersed across Asia, as well as in both Eastern and Western Africa. Its signature is a comparative high share of lightweight low-rise buildings (LCZ-7) and an above average share of low plants (LCZ-D). The share of built-up lands is not high and their proportion is decreasing in favour of vegetation quickly with distance to the centre. This, in turn is reflected in the built-up profile with a cluster being among the less dense overall. The cities have an average size (15.8km).

Last, the purple cluster is mainly located in sub-Saharan Africa. It is noticeable by its low share of built-up land and the highest share, among all clusters, of low plants (LCZ-D) and bare soil or sand (LCZ-F). The two classes account already for almost half of the share in the core layers and become predominant in the outer areas. This is reflected by the extremely low built-up volume of its profile and its small average size (11.6km)

4.2.3 Typology of the concentric model of land use mixture

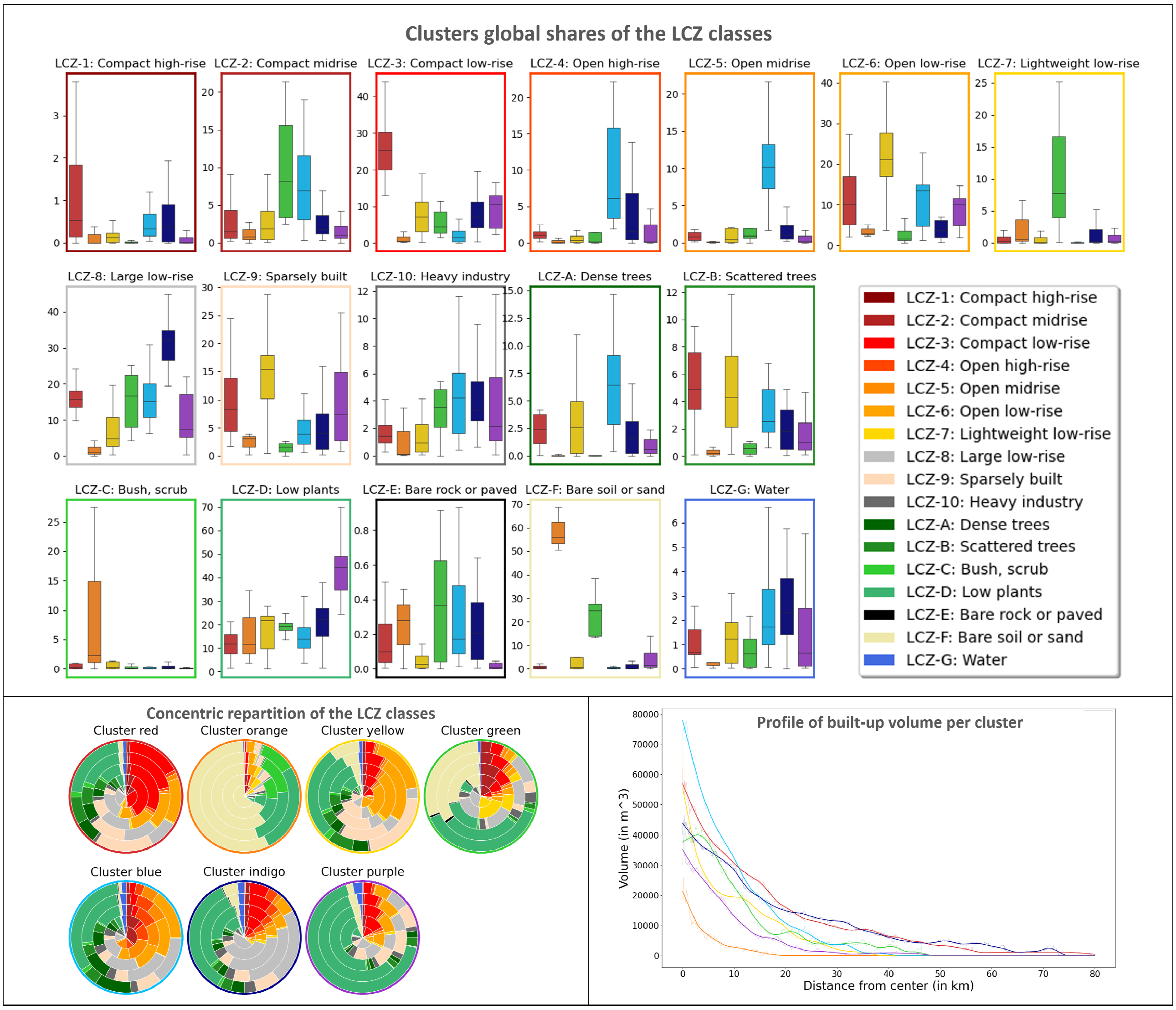

Figure 4: Morphological description of the clusters obtained for the concentric model of land use mixture

The red cluster is mainly located in North and South America, South India and Japan. It is defined by comparatively high shares of compact low-rise (LCZ-3) and scattered trees (LCZ-B) as well as, in lesser proportions, compact high-rise buildings ((LCZ-1). The dense LCZ classes in the core change into sparsely built-up areas (LCZ-9) in the periphery. This, together with a relatively large average size of 21.6km of radius, offers a slow decreasing profile of built-up volume with a long low-density tail.

The orange cluster is represented by three cities which have extremely low shares of built-up land. The cluster is mostly dominated by bare soil or sand (LCZ-F), low plants (LCZ-D) and noticeably bush, scrub (LCZ-C). The proportion of vegetation augments with distance to the centre comparatively to built-up shares. In turn, this results in small sized cities (10.9km) with low built-up volume.

The yellow cluster is mainly situated in Eastern Africa and Asia. This cluster is characterised by a comparatively large share of open low-rise (LCZ-6) and sparsely built buildings (LCZ-9). The core concentric zones are richer in dense built-up classes that change with distance to the centre to the two classes aforementioned. This give a sinuous decline of the built-up volume profile for these average sized cities (14.5km).

The green cluster is mostly located in the Middle East and Somalia. It presents a comparatively high share of compact midrise (LCZ-2) and lightweight low-rise buildings (LCZ-7) with a fair amount of bare soil or sand (LCZ-F). The two built-up classes are mostly packed in the core, increase slightly in the middle layers of the cities and leave place to non-built lands further out. This is reflected in a peculiar built-up volume profile, almost ridging up shortly outside the centre, then decreasing in sinusoidal decay. The cities of this cluster are of average size of 15.4km.

The blue cluster is shared between Europe (prevalent) and inland China. It is defined by comparatively large shares of open high-rise (LCZ-4), open midrise (LCZ-5), and a fairly important share of compact midrise buildings (LCZ-2). Its vegetation presents a higher fraction of dense trees (LCZ-A) than other clusters. The core is composed of compact built-up classes in higher proportions than other clusters. This gives place for almost exponentially higher vegetation shares towards the exteriors. With its average size of 14.9km, the profile of the built-up volume plummets from the highest volumes (in comparison to the other clusters) to a low one in a rapid concave descent.

The indigo cluster cities can be found across Asia and on the shores of Western Africa. It is characterised by its large share of large low-rise buildings (LCZ-8) and the significant presence of water (LCZ-G). The presence of low-rise buildings (LCZ-8) is prevalent across the concentric zones and the substitution of the built-up classes by the non-built-up ones does not affect it. Therefore, we observe for these large cities (21.6km on average) a slow, long-tail decay of the built-up volume profile.

Last, the purple cluster cities are mostly located in sub-Saharan Africa. It is characterised by a prevalence of low plants (LCZ-D) starting from the third concentric zone. The overall richness of non-built-up land is reflected by the low profile of built-up volume. The average size of cities in this cluster is of 13.0km of radius.

5 DISCUSSION

Cities, in their physical faces are diverse. To grasp this diversity, we rely on models of description. Through this study we show that depending on the applied model, the taxonomy of their diversity is not a fixed object; quite the contrary is true: very distinct typologies of cities evolve depending on the feature's spaces. As found in Taubenböck et al., (2020), there is a geographical consistency in the results, for a part that indicates a non-neglectable correlation between cultural regions and similar city types. Nonetheless, this relation varies between the typologies.

Here, it seems that we shed light on the structure of cities through mainly two prisms: By applying unsupervised clustering on three models, the outcomes are significantly consistent between the global model of land-use mixture and the concentric model of land-use mixture. The concentric model of density, however, leads to different categories and thus different geographical distributions. These different types of results when semantically different morphological parameters are used (LCZ in the first type of results and built-up volume in the second case) seems to hint to something else. The density-based approach leads to different types of clusters relying on the repartition of built-up volume across cities. LCZ brings types of buildings, or types of neighbourhood to the front. The latter is more consistent to geographical zones (cf. Fig.1). A hypothesis that relates to this finding is that specific regions of the world witnessed specific ways of development in cities, in the sense that they selected specific architectural support in the process of urban growth (Reference?). We assume that some clusters, which are spread across continents, could point to the fact that these cities also share the same architectural response to growth, at least in their types as defined by the scheme of the LCZs in (Stewart & Oke, 2012). When we study cities of the same clusters that are across different geographical regions, we observe similarities of historical trajectories of urban growth. The similarities are sometime in the nature of their past political governance (e.g.: colonial cities), sometimes on their mode of growth (e.g.: spontaneous or planned). The similarities seem sometimes to be of natures that have already been unveiled in previous works, e.g.: economic importance (Solow, 1973), social relevance (Braunfels, 1976; Kostof, 1991), cultural regions (Ehlers, 1993; Gaubatz, 1998; Griffin & Ford, 1980; Hahn, 2014; Krapf-Askari, 1969; Lichtenberger, 1972), among others.

Against this background, the importance of the ethnical settings in the morphology of the cities has to be nuanced. Further, we argue that rather than speaking of cultural types of cities when studying the similarities and diversities, we should talk about city types emerging from specific contexts of urbanistic culture.

6 CONCLUSION

In this study, we empirically sought to identify groups of cities that share similar morphological manifestations. Through unsupervised clustering of cities across the globe mapped by LCZs and related built-up densities, we pointed out that different models of representation of urban morphologies lead to different typologies of city clusters. This can be observed through their geographical distribution, their types of built-up structures, their spatial distributions and density profiles. An interpretation of the difference of typologies could be that the physical face of cities is influenced by a complex combination of social settings coined here as "urbanistic culture", i.e. how the development of the materiality of the city is typically steered by the multiple agents at stake. In this framework, the results of this study on extracontinental urban similarities could be revisited and further possibilities of influence could be analysed. However, this assumption would need to be proven before we could discuss it further.

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