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Was global urbanization from 1985 to 2015 efficient in terms of land consumption?

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ABSTRACT

Dense cohabitation is associated with higher ecological sustainability and economic benefits than their less dense counterparts. Of course, there are also many challenges associated with high density, but from the perspective of land consumption, the global trend of urbanization is viewed positively. Urbanity and density, however, are and continue to develop very heterogeneously within and between cities. In this study, we analyze morphologic and demographic urban expansion across 1567 major cities around the globe from 1985 to 2015. Thereby, we investigate the changes in the morphological and population densities in the newly built areas in comparison to the status quo in 1985. Furthermore, we use the different densities in cities around the world to design theoretical retroactive scenarios of alternative land consumptions and determine possible carrying capacities. The key findings are: areas built between 1985 and 2015 are less dense in terms of morphology and population than the areas built before 1985. Thus, urban expansion consumed comparatively more land which means that it has become more inefficient with respect to the usage of space. We also find that this inefficiency varies around the globe, with South Asia and East Asia having higher densities in contrast to Europe and North America. The scenarios developed show the unutilized potential: If urban expansion would have been developed more densely, e.g. by 'compact mid-rise' structures, our model calculations show that 1.466 billion more people could live in the same newly built urban areas.

1. Introduction

Urbanization is viewed in the literature as a multidimensional process of physical, demographic, social, economic, political and environmental components in which the benefits outweigh the costs (e.g. Angel et al., 2021; Glaeser, 2010; Hollis, 2013). Cities are, for example, more productive than smaller communities (World Bank, 2022), their innovative strength is higher (Bettencourt, 2007), and land consumption is significantly less than in rural landscapes (Schiavina et al., 2022; Taubenböck, 2021), which leads to better preservation of natural habitats on the peripheries of cities (Johnson & Klemens, 2005). At the same time, however, urbanization also brings the burdens of density. The exposure towards lower air quality (e.g. Erbertseder et al., 2024), the effects of the urban heat island (Leichtle et al., 2023; Lemoine-Rodríguez et al., 2022), traffic congestion (Rahman et al., 2021), among many other issues that have been documented to increase with urban density or, in other words, the challenge to manage density.

Considering both, beneficial and negative aspects of density, it is neither obvious nor clear which type of urbanization we should favor. Against the background of global population growth – by 2050 we will be around 10 billion people (IPCC, 2022) – and the unbroken trend of urbanization – with urban areas now home to more than 56 % of the world's population, and projected to increase to 68 % by 2050 (United NationsDepartment of Economic and Social AffairsPopulation Division, 2018) – we need to ask ourselves how we want to develop the cities of the future.

In this study, we aim to lay the groundwork to empirically frame this central question based on multitemporal building structural developments in cities across our planet. Although the dynamics of global urbanization in its physical and demographic manifestations have been documented in manifold studies (e.g. Angel et al., 2011; He et al., 2019; Huang & Xu, 2022; Seto et al., 2011; Taubenböck et al., 2012; United

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NationsDepartment of Economic and Social AffairsPopulation Division, 2018) and regional differences in their dynamics have been identified (e.g. Güneralp et al., 2020; Huang, Li, Yang, & et al, 2021; Liu et al., 2020; Melchiori et al., 2018; Taubenböck et al., 2024), there is no systematic, global study of the structural forms at intra-urban level analyzing in which this urban expansion has taken place.

Even if cities are primarily defined by people (Gehl, 2009; Jacobs, 1961) and the complex networks, material flows and exchanges (Batty, 2013; Inostroza & Zepp, 2021; Sassen, 2002), all of this is embedded in the physical built space. The built and natural urban spaces form the basis for actions, everyday rhythms, etc. and thus have a great influence on the livability as well as the sustainability of a city (e.g. Sennett, 2018, p. 368; Tonkiss, 2013).

Buildings, streets, plots, and open spaces can be seen as the basic ingredients (Kostof, 1991; Salat, 2011) of the built urban space or '*technomass*' (Inostroza & Taubenböck, 2024). Combinations of these ingredients, just like DNA, turn into unique configurations with no two cities across the world being identical. Many studies have demonstrated the variability of built structures and patterns in cities across the globe: From theoretical observations (e.g. Burgess, Park, & McKenzie, 1925; Hoyt, 1939; Harris & Ullman, 1945) to various models (e.g. Alonso, 1964; Garreau, 1991; Vance, 1964), to empirical studies measuring and comparing the built space and its urban patterns (e.g. Schneider & Woodcock, 2008; Frolking et al., 2013; Braun et al., 2023; Huang et al., 2007). With an improved availability of global remote sensing data and new possibilities for evaluation using AI techniques (e.g. Gong et al., 2020; Sun et al., 2022; Zhou & Weng, 2024; Zhu et al., 2022), data sets that make these empirical studies possible are now available. These range from multi-temporal global classifications of settlement evolution (e.g. Huang, Li, Yang, & et al, 2021; Marconcini et al., 2018; Pesaresi et al., 2015; Zhou et al., 2018) to intra-urban classifications of the built landscape (e.g. Bechtel et al., 2015; Demunzere et al., 2022; Li et al., 2022; Zhu et al., 2022). Approaches to documenting the intra-urban configurations of built landscapes are based on parameters such as building density, heights or types (e.g. Taubenböck, Kraff, & Wurm, 2018; Xu et al., 2019; Liu et al., 2024), the fragmentation of urban landscapes (e.g. Angel et al., 2012; Liu et al., 2022) or the spatial arrangements in complex or ordered geometric patterns (e.g. Lemoine-Rodríguez et al., 2020; Debray et al., 2023). The variability of structural city configurations was empirically proven and structural city types were identified (e.g. Thomas et al., 2012; Taubenböck et al., 2020; Iungman et al., 2024). It therefore stands to reason that not only are cities as a whole structurally different, but that expansion in recent decades has also brought about structural differences.

Given the documented variety of structural configurations in space, it is likely that this variation also exists over time due to the shifting of certain paradigms: for example, changes in construction technology have impacted the nature of architecture (Mumford, 1934, 1961). Another example is demographic change, which has been shown to affect the viability of certain infrastructures (Siedentop & Fina, 2010) and thus influences urban development (Schneider & Woodcock, 2008). A further example is the change in planning paradigms, which is proven to have a significant impact on urban structures (Debray et al., 2023). These can be seen, for example, in the implementation of regulations, i.e. development plans, ordinances or planning codes (Kostof, 1991) or the change of ideologies that planning follows (Taubenböck, Murawski, & Wurm, 2018; Kostof, 1991). This temporal dimension of variety in intra-urban structure, however, has not yet been empirically researched at a global level.

In this study, we therefore aim to specifically analyze urban expansion in terms of morphological-structural developments over 30 years for all 1567 cities larger than 300 000 inhabitants. Our approach focuses on four aspects of urban expansion over the period 1985–2015. *First*, we characterize quantitatively the urban fabric, here operationalized by the Local Climate Zones (LCZs) (Stewart & Oke, 2012), of the yearly additions to the built-up area of the cities. *Second*, we quantify the differences between the state of the urban fabric of the cities in 1985 and in 2015. *Third*, we compare the population density in both, the old and the newly built-up areas while controlling for the same LCZ type. And *fourth*, we provide scenarios for comparison to how urbanization occurred over the 30 years of monitoring, i.e. we calculate how many people could have become urban dwellers if the urban structures would have been developed in a denser or less dense way.

In all these analyses, we unravel the morphological variability of urbanization across regions by grouping cities at the global level as well as on the level of continents and geographic regions. For the latter, we apply regions defined by the Intergovernmental Panel on Climate Change (IPCC). The empirical results should then lay the foundation to show how cities typically and, if necessary, regionally had grown in terms of morphological structure from 1985 to 2015 and what the consequences would be if this trend would continue over the next 30 years.

2. Conceptual foundation

Global studies on the expansion of urban settlements rely mostly on a binary understanding of the '*urban*' as built-up, artificial land cover vs. natural landscapes (Angel et al., 2011; Melchiori et al., 2018; Huang, Li, Yang, & et al, 2021; Taubenböck et al., 2024; among many others). Fig. 1a illustrates the settlement expansion for three sample cities of varying dynamics based on this dichotomic classification.

The terms '*city*' or '*urban*', however, conceal very different forms of morphological design. Morphological differences in cities across the globe range, for example, from nearly 90 % building density – if you like, an almost complete usage of space – and population densities estimated at about 500 000 people per square kilometer in slums (Taubenböck, Kraff, & Wurm, 2018) to low-density, low-rise detached, single-family housing developments with about 10 % building density and only 450 people per square kilometer (Ottensmann, 2020). Thus, the terms '*city*' or '*urban*' subsume in these morphologic appearances a large variability of structural compositions of land cover and usage intensities. In previous studies, urban expansion has not been mapped at this intra-urban structural differentiation, but in dichotomous classifications. A long-term study of urban expansion with a higher resolution on intra-urban structural differences is still absent (Zhu et al., 2019). This is mainly because intra-urban structure classifications have only recently become possible with increased resolutions of satellite data and better methods on a global level (Zhu et al., 2022; Demuzere et al., 2022).

Even if such a multi-temporal global study is lacking, there are manifold studies documenting the large variability of morphological settlement structures (e.g. Conzen, 1980; Kostof, 1992; Lynch, 1984; Salat & Bourdic, 2012, pp. 97–107). These works introduce the various logics, processes and theorized ideas shaping the various urban morphologies. Various studies attempt to make the structures empirically tangible and comparable by means of spatial metrics (e.g. Batty, 2005; Boeing, 2019; Fleischmann, Romice, & Porta, 2021). Further studies monitor trends and attempt to interpret and compare the developments in urban morphology. Lemoine-Rodríguez et al. (2020) document a global trend towards homogeneous urban form. Debray et al. (2023) measure characteristic spatial features that point towards the intensity of plannedness of specific structural city appearances. Taubenböck, Kraff, and Wurm (2018) reveal the variety of physical appearances within one target class of '*arrival cities*'. Beyond such studies, there have been conceptual approaches towards the classification of urban structure types that have been operationalized: The European Urban Atlas, for example, provides a uniform mapping scheme for urban structural types applied to all cities across Europe larger than 100 000 inhabitants (EEA, 2024). The National Land Cover Database (NLCD) is another example featuring different intensity classes for developed areas in the United States of America (NLCD, 2025). One widely accepted concept to map the structural composition of cities are Local Climate Zones (LCZs). The LCZs classification frame is a generic, culturally-neutral description

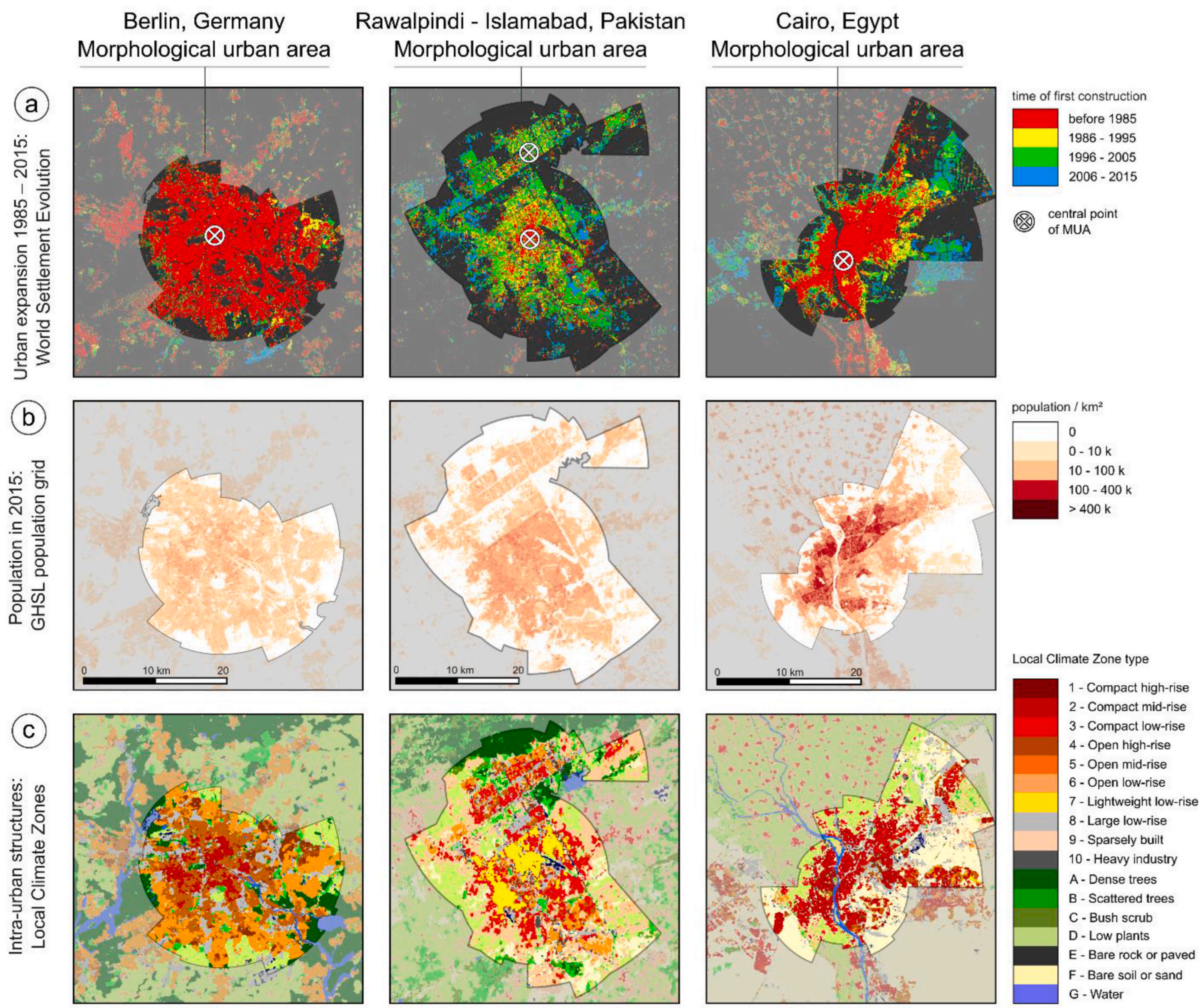

Fig. 1. Data sets used and illustrated for the examples of Berlin, Germany, Rawalpindi-Islamabad, Pakistan and Cairo Egypt. The standardized morphological urban areas (MUAs) (Taubenböck et al., 2019) are used as data-driven consistent delineation of cities. a) Urban expansion 1985–2015 using the World Settlement Evolution layer. b) Population distribution using the Global Human Settlement layer. c) Intra-urban structure using the LCZs classification scheme in 2015.

of morphologic-structural realizations of land-use and land-cover (Stewart & Oke, 2012). A variety of studies attempted to map LCZs at large scales (e.g. Bechtel et al., 2015) or even globally (e.g. Zhu et al., 2022). The latter data set, for example, has been the basis to categorize and compare the variability of morphologic city configurations across the globe (Taubenböck et al., 2020). Fig. 1c reveals various intra-urban morphological configurations using the three sample cities.

Against this background and in contrast to previous studies, we focus here on the urban areas that were newly urbanized from 1985 to 2015, i.e. previously undeveloped land that was transformed into urban areas through expansion. We specifically focus on the structural forms in the expansion areas. While the urban fringe where most expansion takes place is commonly associated with low-density, low-rise development, we examine globally whether this association stands up to empirical investigation. The higher-ranking idea in this paper is to document the morphological-structural types of urban expansion between 1985 and 2015. In a thematic perspective, we ask whether urban expansion was sustainable in terms of land consumption.

3. Data

For the analysis, we utilize a set of various data: The *World Settlement Footprint Evolution,* a global *local climate zones* classification*, morphological urban areas,* population data from the *Global Human Settlement Layer* and data on *geographic units* (i.e., continents and geographic regions).

For capturing spatial urban expansion, we rely on the *World Settlement Footprint Evolution* (WSFEvo) (Marconcini et al., 2018) which is based on Landsat data. The mapping product provides the settlement extent at 30m spatial resolution on a yearly basis from 1985 to 2015 at global scale. Fig. 1a visualizes the expanding settlement patterns as mapped by the WSFEvo by the examples of the metropolitan regions of Berlin, Germany, the urban agglomeration of two administratively separate cities – Rawalpindi and Islamabad in Pakistan – which have morphologically grown together into one city, and Cairo, Egypt. The three cities illustrate the variety of urbanization dynamics across regions of the world.

For the analysis of intra-urban structural configurations, we rely on the *global local climate zones classification* as provided by Zhu et al. (2022). This data set is based on Sentinel-1 and Sentinel-2 satellite data. The LCZ classification scheme is a generic and neutral description of land-use and land-cover (Stewart & Oke, 2012). The classification scheme relies on universal, standardized and measurable parameters of urban form such as 'density', 'building size' and 'building height' for the built landscape, as well as trees, low vegetation, open spaces and water for the non-built landscape. Fig. 2 illustrates this conceptualization of structural types. The arrangement of the LCZs in the figure is organized according to '*high density (compact)*' and '*low-density (open)*' structural types, as this plays a methodological role later on. The numbering of the LCZs is based on the work of Stewart and Oke (2012). Fig. 1c exemplifies the intra-urban LCZs structures for Berlin, Germany, Rawalpindi-Islamabad in Pakistan, and Cairo, Egypt. In this study, we assume that the LCZs of today also correspond to the LCZs of built areas in 1985. We also assume that in the newly built areas, the LCZ types that we measure today have not changed over the course of the 30 years. We have to use this conceptual simplification because LCZ classifications are not available for 1985.

For population information, we rely on the *Global Human Settlement Layer* (*GHSL POP data)* (Schiavina et al., 2023). It provides population information at a 100m resolution. The approach is based on disaggregating population data from censuses to a high granular resolution with the knowledge of settlement locations and respective building volumes. In this study, we rely on data for 1985 and 2015. Fig. 1b illustrates the population data for our three sample cities.

As administrative units of cities do not allow for a consistent comparison across cities (e.g. Brenner & Schmid, 2013), we use here a spatial reference unit that delineates cities across the globe in a data-driven way. City boundaries have been delimited for the year 2015 (for details on data and methods, we refer to Taubenböck et al., 2019) using the Global Urban Footprint (GUF) and the GUF Density (GUF-DenS) data sets (Esch et al., 2018). From it, an urban-rural gradient is used to delineate the '*urban*' from the '*rural*' in a consistent way for all cities of our sample. These units are called '*morphological urban areas*' (MUAs) and are illustrated in Fig. 1.

Our sample consists of 1567 cities larger than 300 000 inhabitants in 2015 (United Nations& Department of Economic and Social Affairs, 2015). While in the United Nations database, 1692 cities worldwide were recorded with more than 300 000 inhabitants in 2015, our data set is reduced to 1567 cities as the data set provided by Taubenböck et al. (2019) counts cities that spatially coalesced into metropolitan regions as one city. The two administratively separate cities – Rawalpindi and Islamabad in Pakistan illustrated in Fig. 1 have morphologically grown together and are in this conceptual approach counted as one city. These largest cities in the world cover 19.9 % of the entire global settlements in 2015. However, more than 27.3 % of the global population live there. These numbers demonstrate that this comparatively small area can have enormous leverage effects such as the land consumption analyzed in this study.

For the analysis of spatial variabilities of structural urbanization processes across the globe, we relate to the six *continents*, i.e. Africa, Asia, Europe, North America, Oceania and South America. In addition, we relate our analysis to ten *geographical regions* as suggested by the IPCC Working Group III in its Fifth Assessment Report (Krey et al., 2014). Here, we use the region categorization 10 (RC10). These correspond to Western Europe, Economies in Transition (Eastern Europe and part of former Soviet Union), North America, Pacific OECD (Japan, Australia, New Zealand), Latin America and Caribbean, Sub-Saharan Africa, Middle East and North Africa, East Asia, South Asia, and South-East Asia and Pacific (IPCC, 2014).

4. Methods

4.1. Indicators for measuring structural urban expansion trajectories

We use two measures characterizing the trajectory according to which urban expansion was physically structured: First, for each year between 1985 and 2015, we retrieve the spatial extent of the newly built-up area of the particular year (cf. Fig. 1a). For each of these incremental newly built-up areas, we retrieve the corresponding LCZs (cf. Fig. 1c). From it, we compute the spatial share of each built-up LCZ class. Comparing this year on year, we show to what extent the incrementally added urban fabric resembles or departs from the original structural status quo of 1985. Second, we compute the absolute changes in the share of each built-up LCZ class for the cities between their 1985 extent and their 2015 extent. With this, we aim to quantitatively evaluate if the cities have changed in their general structural configurations or if they have remained the same.

4.2. Population densities at LCZ level at particular time steps

The LCZs of the built landscape approximate the density in 2D and 3D of the urban structure (cf. Fig. 2). Because all or parts of the floor

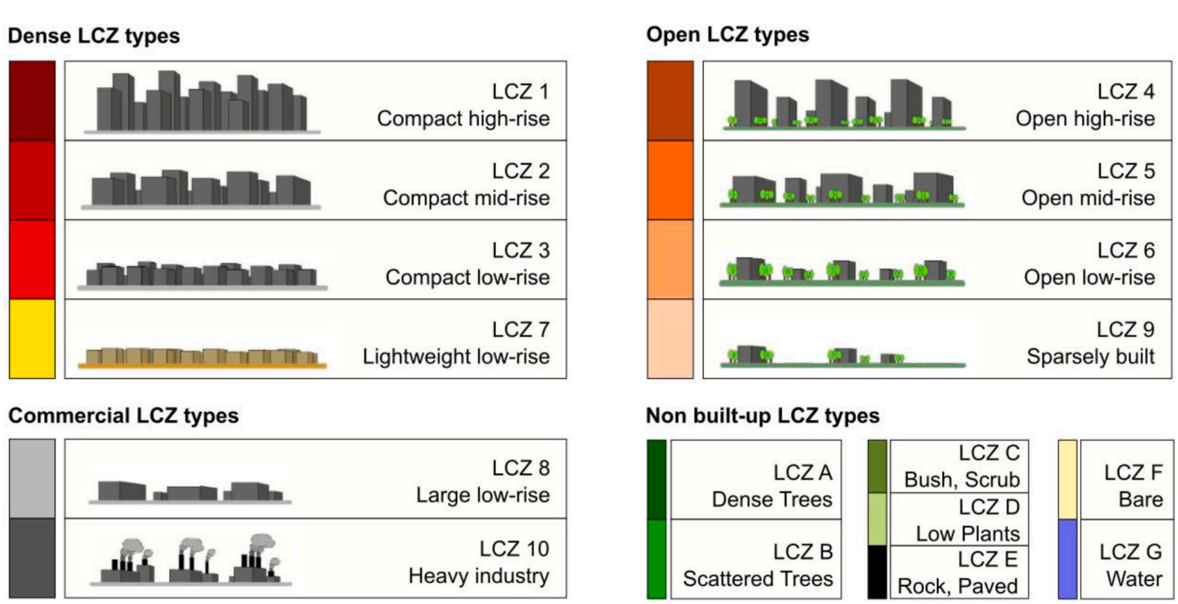

Fig. 2. Local Climate Zones (LCZs) – 17 types of a generic, culturally-neutral description of land-use and land-cover (based on Stewart & Oke, 2012).

space is used as residential space, population densities correlate with these structures to a certain degree (e.g. Sapena et al., 2022). However, building usages are often decoupled from building types or volumes or usage efficiency changes due to changing behaviors such as residential space consumption. Therefore, it cannot be assumed that the correlation is linear and we need to be aware that it also varies over time. With this in mind, we aim to measure the development of population densities in the urban areas considered, while controlling for physical density of the urban fabric.

To do so, we operationalize our analysis of the evolution of the population density at LCZ level over time. We combine the multi-temporal population figures of the GHSLpop dataset with each individual LCZ built-up class. First, we calculate this only for the newly built areas between 1985 and 2015. Therefore, we use GHSLpop from 2015 and calculate the population density per LCZ. Second, we use the GHSLpop dataset from 1985 to calculate the densities for the starting year of the analysis. We calculate this for the LCZs in urban areas that existed already in 1985. Third, and finally, we calculate the population densities per LCZs for the entire respective city for 2015.

With these three measures, we aim to 1) compare whether the population densities measured in 2015 are similar or different at LCZ level between the newly developed urban areas and the areas developed prior to 1985. 2) In addition, we aim to see how the population densities in the city have changed from 1985 to 2015, within the 1985 areas, as well as at LCZ level for the entire city.

4.3. Exploring potential population capacities of urban expansion 1985–2015

It is clear that different structural forms of development have very different carrying capacities in terms of population. While urban living is seen as living in densification, urbanization is seen as more efficient than rural structures in terms of land consumption (e.g. Glaeser, 2010). Nevertheless, population densities are highly variable: Across the globe the same LCZs might have very different population densities due to different economic, socio-demographic or cultural backgrounds in different regions. Accordingly, the question of whether urban expansion was sustainable in terms of land consumption is not so easy to answer.

Our aim is therefore to estimate the theoretical carrying capacity of the newly built areas between 1985 and 2015. We model what the carrying capacity would be if a structural type with higher or lower population density would have been built.

We basically use four approaches for the scenarios: 1) *Single structural type expansion*; 2) *Structural type specific adaptions*; 3) *Statistical models*; and, 4) *literature-based models*.

1) For the *single structural type expansion*, we assume that the entire urban expansion area between 1985 and 2015 would have been built on with one LCZ, i.e. denser or less dense than in reality, depending on the area. We then derive the theoretical carrying capacity from the average global population density of this particular used LCZ. Subsequently, we use these densities to model the carrying capacities of the de facto expansion areas between 1985 and 2015 with only this one LCZ – denser or less dense – at a time. The result then shows in theoretical manner how many more or fewer people could have lived in the same area if a single type of structure would have been built. Of course, this is a very theoretical thought experiment, as the new settlement area would never completely consist of just one type of structure.
2) With this in mind, we are also developing '*structural type specific adaptation*' scenarios which we consider to be more realistic, as a structural change to slightly denser/less dense or slightly higher/less high built-up structures corresponds to either planning interventions or informal developments that also take place in reality. In four scenarios, we assume in the model calculations that the existing LCZs would have been implemented one structural type denser/less dense or higher/less high (Fig. 3). As example, the LCZ type 'compact high rise (LCZ1)' would be consistently less dense, i.e. 'open high-rise (LCZ4) (Scenario A – Decrease in density). Conversely, we also calculate the inverse scenarios of density increase: e.g. 'open-high rise (LCZ4)' would be consistently built denser as 'compact high-rise (LCZ1) (Scenario B – Increase in density). This is also implemented analogously for the other LCZs in terms of density and for the height of the structures to address the multiple possible scenarios (Fig. 3).

All these scenarios are calculated using the LCZ-specific population densities at the regional level. For example, the conversion of 'open low-rise' to 'open mid-rise' in East Asia projects the population densities of 'open mid-rise' in East Asia, rather than the global one, to the area of 'open low-rise' in East Asia.

3) In addition, we also use *statistical models* relying on de facto population densities from the complete data set. Based on the GHSL pop, we calculate population densities among our 1567 cities. We calculate quantiles of population density, i.e. the 1 %, 5 %, 10 %, 50 % (median), 90 %, 95 %, and 99 %. We then use these population densities to calculate how many people could live in the expansion areas from 1985 to 2015.
4) And, we apply different population densities as provided by *literature.* Here we rely on densely populated areas such as in slums in Nairobi (more than 48 000 p/km^2) (based on Hu et al., 2021), Mumbai (19 865 p/km^2) (based on United Nations Department of Economic and Social Affairs, 2016) or New York City (10 948 p/km^2) (based on United Nations Department of Economic and Social Affairs, 2016) as well as on very low-density areas such as suburbs (819 p/km^2) (based on Ottensmann, 2020), or a particular low dense case such as in Pittsburgh (459 p/km^2) (based on Ottensmann, 2020).

5. Results

The 1567 cities with more than 300 000 inhabitants in 2015 had a combined built-up area of 140 810 km^2 in 1985. 30 years later, in 2015, the total built area within the MUAs increased by 120 469 km^2 to 261 278 km^2 and thus almost doubled. This expansion of the built-up area considering only these largest cities on our planet corresponds to around one and a half times the area of Austria or three times the area of Switzerland. This shows how dynamically the large cities of our planet have grown.

1.168 billion people lived in these cities in 1985. Until 2015, the total population within the MUAs increased by 844.87 million people, with 729.82 million in the newly built areas. This means that the population in these large cities has increased by almost twice the current population of the European Union, about two and a half times the population of the USA or over 10 times that of Germany.

These numbers show the dynamics and dimensions of urbanization in these large cities. Now, the questions arise as to which built structures this urbanization has taken place in since 1985 (section 5.1.), whether these newly built structures differ from the structures of the cities of 1985 and, if so, how they differ (section 5.2.), how population densities have developed overall and in the respective LCZs (section 5.3.) and what theoretical carrying capacities do the expansion areas have if other densities would have been realized (section 5.4.).

5.1. Urban expansion with increasing shares of low dense built-up structures from 1985 to 2015

The urban fringe where the majority of the urban expansion takes place is generally associated with structures of low-density and low building heights. We can indeed see that this association stands up to global empirical investigation. Urban expansion has been carried out with increasing shares of low dense built-up structures from 1985 to 2015.

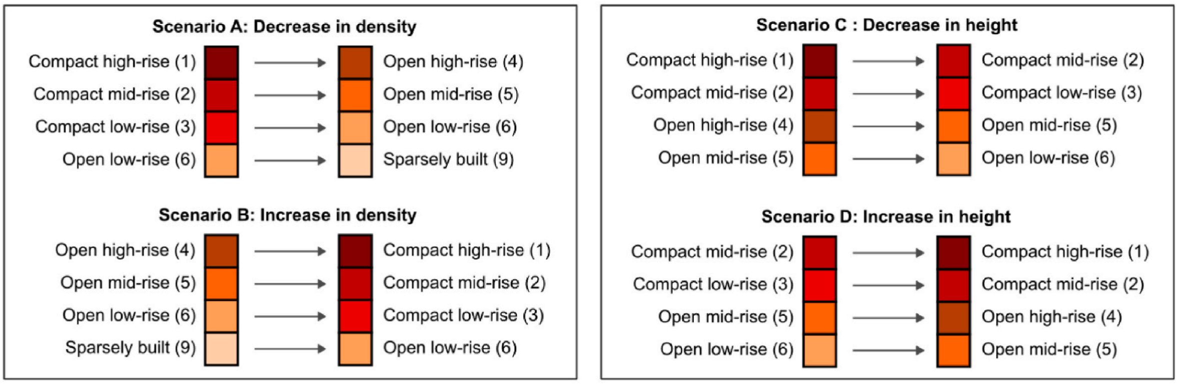

Fig. 3. Four scenarios of '*structural type specific adaptation*': Scenarios A and C depict a decrease in building density and height and Scenarios B and D depict an increase in building density and height.

We observe decreasing shares of dense built-up types (LCZs 1, 2, 3) across the globe over the monitoring period in the expansion areas (Fig. 4). Whereas at the beginning of the monitoring period around 1985, almost 25 % of all new-built sites globally were dense LCZs, this had fallen to just over 6 % by 2015. Sparsely built areas (LCZ-9), in turn, have been established in an increasing manner. They had only a share of about 6 % around 1985, but are today the dominating newly added structural type with almost 33 %. It is particularly noteworthy that in the expansion areas, all low dense LCZs (LCZs 4, 5, 6, 9) combined are today the dominating added structural types with about 63 %.

Of course, structural developments are not equally distributed around the world. At continental scale, we measure that in particular in Europe 'dense' LCZs (LCZs 1, 2, 3) are almost no longer being built for urban expansion (around 1 % only). Although we are also seeing a decline in this class on all other continents, at least around 5 % of space is still being densely built in this way in Asia, North America and Africa. This type of structure still accounts for around 10 % of the most recently built areas in Oceania and South America in 2015. It is particularly noteworthy that in South America at the beginning of the monitoring period, 'dense' LCZs were the dominant structural type of urban expansion with over 40 %. With respect to low dense LCZs (LCZs 4, 5, 6, 9), it is striking that the contributions of these LCZs are increasing on every continent. In Africa, for example, the shares of 'sparsely built' (LCZ-9) increased from almost zero in 1985 to more than 62 % in 2015. Combined with the other low dense classes, this type is dominant in urban expansion (about 88 %) in Africa. In North America, Europe, Oceania and South America the shares of the low dense LCZs (LCZs 4, 5, 6, 9) in newly built areas add up for 2015 to around 70 %. Only Asia features among the low dense classes just about over 50 % of shares in 2015. It is worth pointing out that 30–40 % of Asian expansion is related to the 'large low rise' LCZ (LCZ-8) which is substantially more than in any other area.

If we differentiate such large areas as continents according to IPCC regions, certain special features become apparent: In South Asia, Latin America and the Caribbean, and Sub-Saharan Africa the 'lightweight low rise' LCZ (LCZ-7) which is conceptually very close to slums or informal settlement structures reveal a notable share (26 %, 6 % and 5 %, respectively) of newly built areas in 1985. However, the added share of this particular LCZ is decreasing over time. It is also interesting to see that compact urbanization (LCZs 1, 2, 3) played a significant role in Latin America and the Caribbean (about 44 % in 1985), South Asia (ca. 36 %), South-East Asia and Pacific (ca. 31 %), East Asia (ca. 26 %), Pacific OECD (ca. 25 %), the Middle East and North Africa (ca. 25 %) and to a certain degree also South Saharan Africa (ca. 21 %) and in North America (ca. 17 %). In comparison, in Western Europe compact structural developments had only a share of about 11 %. In general, however, dense urban developments have decreased across all IPCC regions. In Western Europe, these developments decreased over the monitoring period from about 11 % to about 1 %, i.e. there is almost no compact development in newly urbanized areas anymore.

5.2. Structurally less dense cities in 2015 than in 1985

The fact that the expansion areas have been built increasingly with low density LCZs (section 5.1.) has also changed the overall structure of cities compared to 1985. The cities in 2015 are on average structurally less dense than in 1985. The proportion of dense, compact LCZs (LCZs 1, 2, 3, 7) has decreased globally from 32 % to 26.1 %, while the proportion of low-dense, open LCZs (LCZs 4, 5, 6, 9) has increased from 37.7 % to 40.5 % (Fig. 5).

We generally see this trend towards fewer area shares of dense, compact LCZs on every continent, but the trend is particularly pronounced in Asia (from 38.6 % to 26.7 %), Africa (from 37.2 % to 31.1 %) and South America (from 56.7 % to 49.5 %). Conversely, the strong increase in the low-dense, open LCZ types is particularly noticeable in Africa where it increased from 44.4 % to 53.3 %, in Asia, where it increased from 26.6 % to 32.1 % and in South America where it changed from 21.9 % to 30 %. 'Sparsely built up' also increased in North America (from 42.4 % to 45.7 %).

This trend of a relative decrease in dense, compact LCZs can also be constantly observed in the IPCC regions. The trend is strongest in East Asia (from 30.8 % to 18.1 %) and South-East Asia and Pacific (from 48.3 % to 37.8 %) and Latin America and Caribbean from 53.7 % to 46.5 %.

The proportion of commercial LCZs (LCZ 8, 10) remained comparatively stable in most regions, with the notable exceptions of East Asia where it increased from 38.5 % to 48.9 % and Sub Saharan Africa where it decreased from 18.2 % to 14.7 %.

Fig. 5 shows an overview of these multi-temporal structural changes structured by the entire world, continents and IPCC regions.

5.3. Demographic densification in cities despite low densities in the expansion areas

The analyses have shown that urban expansion has led to lower structural densities in the 1567 largest cities worldwide over the 30 years of monitoring from 1985 to 2015 (cf. section 5.1. and section 5.2.). However, the question arises as to whether this is also accompanied by lower population densities and, in particular, how population densities have developed within certain LCZs.

We find that population densities have slightly increased at the level of the entire cities with 5681 inh./km^2 in 1985 to 5948 inh./km^2 in 2015. However, there are major differences in population densities between the urban area that already existed in 1985 and the expansion areas that were built between 1985 and 2015. The areas that were already built-up in 1985 have increased in population from 970.2 million to 1281 billion and in population density from 5681 to 7500 inh/

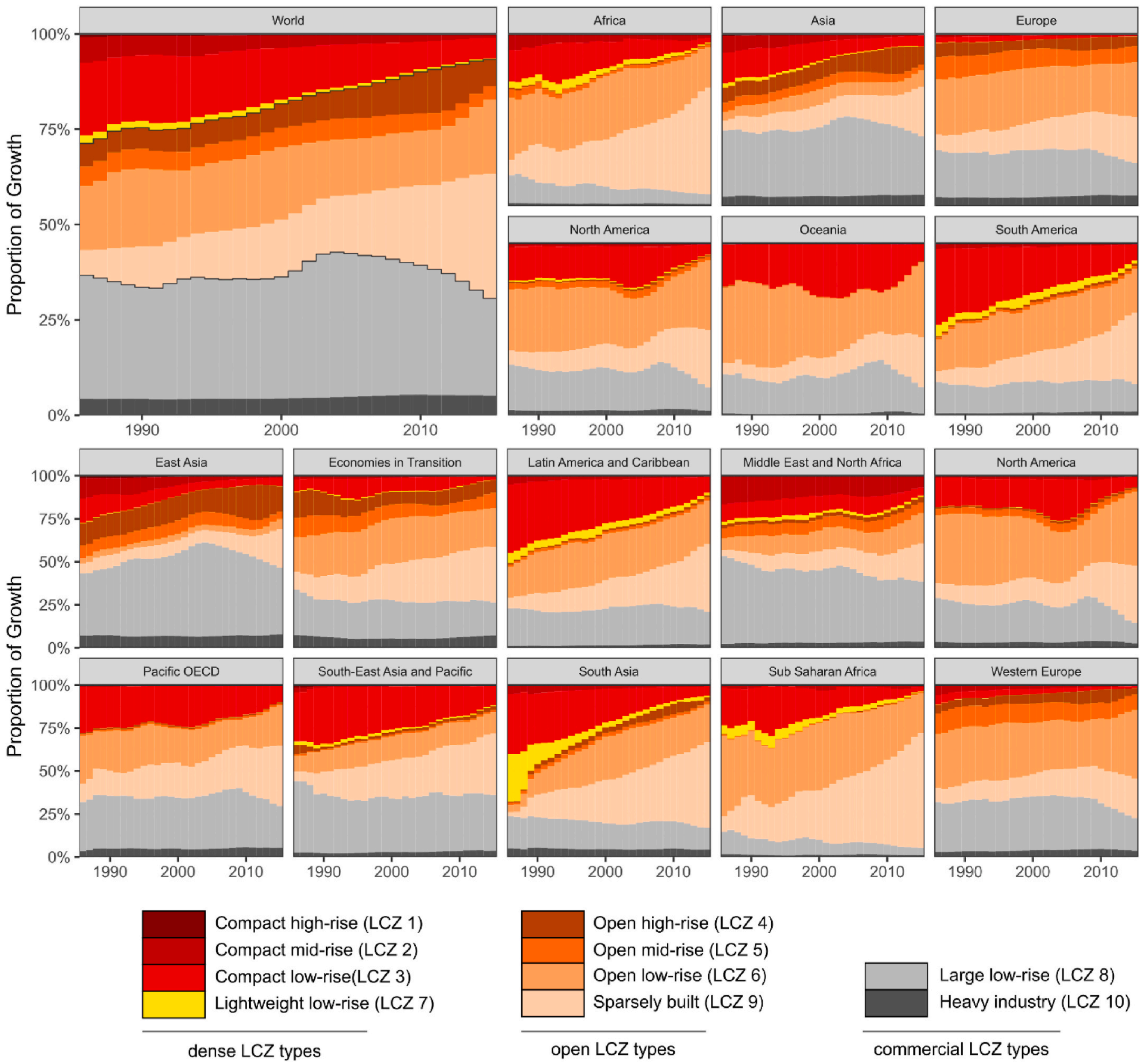

Fig. 4. The share of LCZs in the newly urbanized area in a yearly progression from 1985 until 2015 aggregated to the world, continents and IPCC regions.

km^2. The newly built urban areas from 1985 to 2015 add 720.8 million people to the urban population. However, the population density in these expansion areas is with 4349 inh./km^2 at a substantially lower level. Overall, this shows that the urban expansion areas have a lower building density and correspondingly a lower population density than the areas that existed in 1985 already. Nevertheless, it must be stated that for the entire cities the densification of the population in the older urban areas has more than compensated for the low density in the expansion areas.

Distinguishing these developments in population density by LCZ, we measure that more dense, compact built-up LCZs (LCZ 1, 2, 3 and LCZ 7 'lightweight low-rise', the latter being a proxy for slums and informal settlements) have, as assumed, the highest population densities worldwide (Fig. 6).

This relation between the built densities and population densities are also mapped at continental level. However, there are significant differences in population densities between the continents for the same LCZ. Population densities in the 'compact mid-rise' LCZ (LCZ-2) are around 15 000 inh/km^2 in Europe and Asia. In North America or Oceania, however, they are only around 5000 inh/km^2. At the level of the IPCC regions, the population densities in South Asia stand out with around 28 000 inh./km^2 at the 'dense, compact' LCZs. In contrast, North America stands out here with the lowest population densities of around 3000 inh./km^2.

It is particularly interesting that over the course of time, population densities of the respective LCZ class are consistently lower in the areas that were added between 1985 and 2015. For example, in 2015, the LCZ class 'compact mid-rise' (LCZ-2) shows a population density of approx. 20 100 inh/km^2 in the areas that were already built on in 1985. For the same class, we measure a density of only 13 700 inh/km^2 in areas built since 1985. And this trend applies to almost all LCZs (Fig. 6).

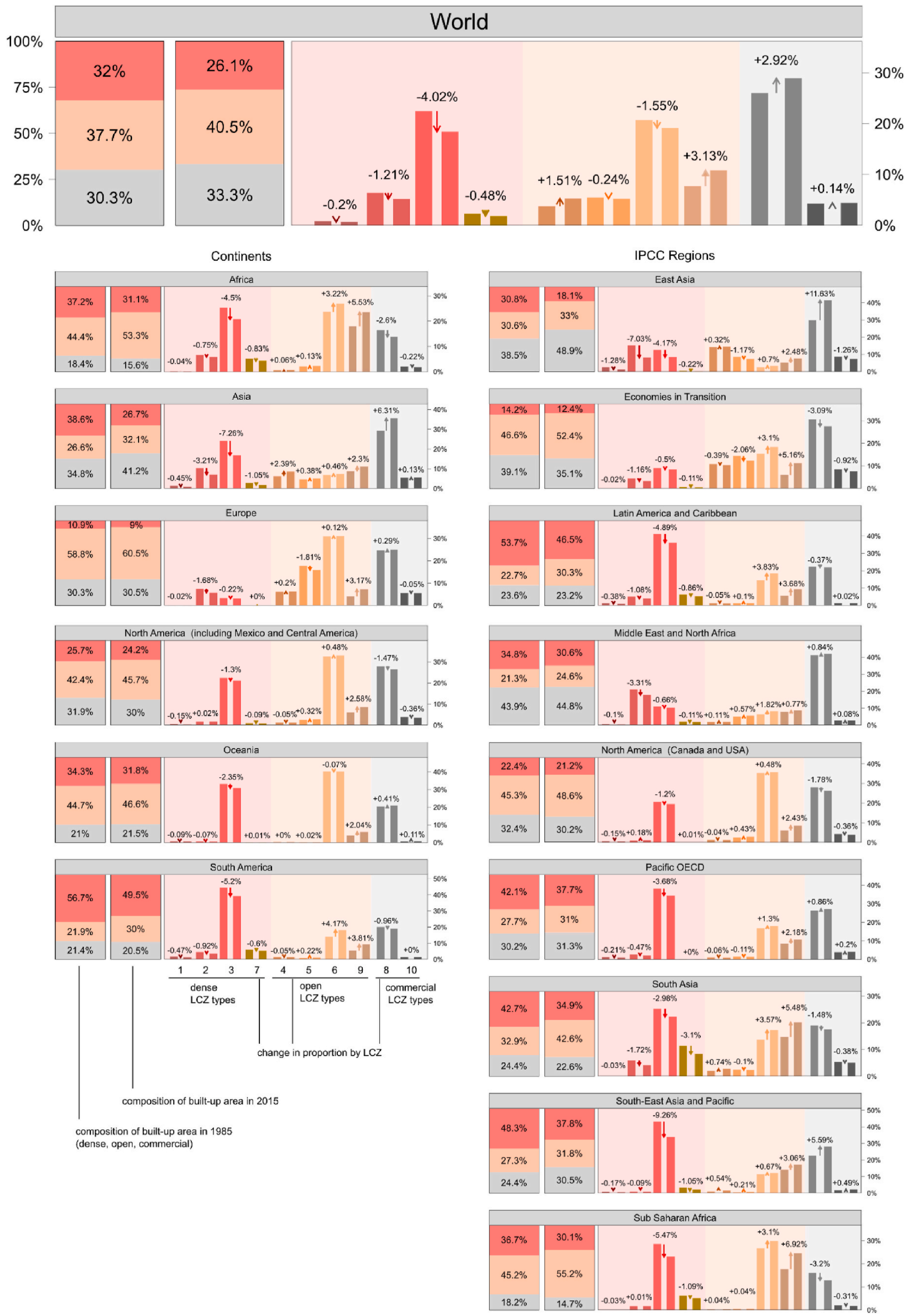

Fig. 5. The shares of built LCZs and their comparison 1985 to 2015 aggregated to the world, continents, and IPCC regions.

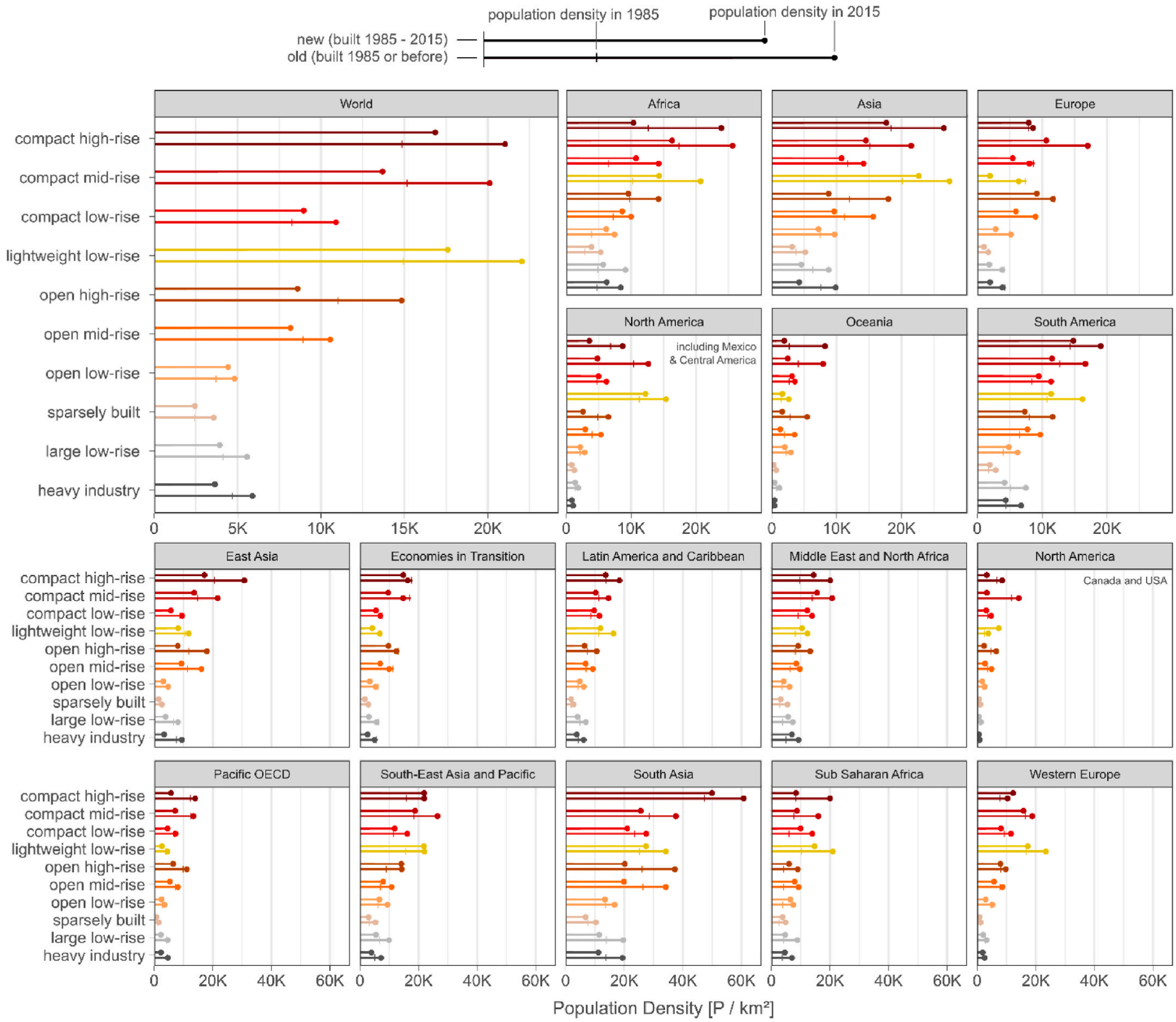

Fig. 6. Population densities for LCZs at global, continental and IPCC region level and over time, 1985 and 2015.

5.4. The great untapped potential: scenarios of land consumption in expansion areas considering theoretical population carrying capacities

Urbanization is seen as the path to less land consumption. Nevertheless, we have seen that very different structures have been realized within the built landscape. And these different structures have different carrying capacities for population. In particular, we have seen that low dense LCZs have dominated the expansion process of cities from 1985 to 2015 (cf. section 5.1.). The 1567 cities larger than 300 000 inhabitants in 2015 carry now an additional urban population within their MUAs of 844.87 million people. Whether this is efficient or not is not easy to answer.

With model calculations, we aim to provide an approximation of this question. The model calculations show that a significantly higher carrying capacity in the urban expansion areas would theoretically be possible, and thus there is a great untapped potential (Fig. 7): With *single structural type expansion* scenarios, we model if the urban expansion areas were not dominated by low-density LCZs (LCZs 4, 5, 6, 9), but were built exclusively with higher densities. For example, 'compact mid-rise' LCZs (LCZ-2), having on median a population density of 13 193 inh/km^2 across the globe, would allow 2.187 billion people to live there, i.e. an additional 1.466 billion people.

Of course, building the entire urban areas in a homogeneous structural style – as simplistically assumed in the model above – is neither practical nor aesthetic. Therefore, *structural type specific adaptation* are model calculations that come closer to reality, i.e. if each LCZ in the expansion areas were increased by one structural density level. With this single stage increase in density, the same newly built urban area in the observed MUAs can provide a home for an additional 232 million people (cf. Scenario A in Fig. 3). This is around the magnitude of a country the size of Pakistan or Nigeria. Alternatively, 24.6 % of the space could have been saved and used for other purposes or as natural environment. Building higher instead of denser could have had a similar effect, providing housing for 119 million people more (cf. Scenario B in Fig. 3).

If we go one step further and detach the analysis from a structural type and take as *statistical model* the top 10 % of population density within all MUAs, then we could reach 15 128 inh/km^2. This means that 2.507 billion people could live in these expansion areas – and with it far more than double the population could actually be added.

And finally, model calculations using extremes based on *literature*

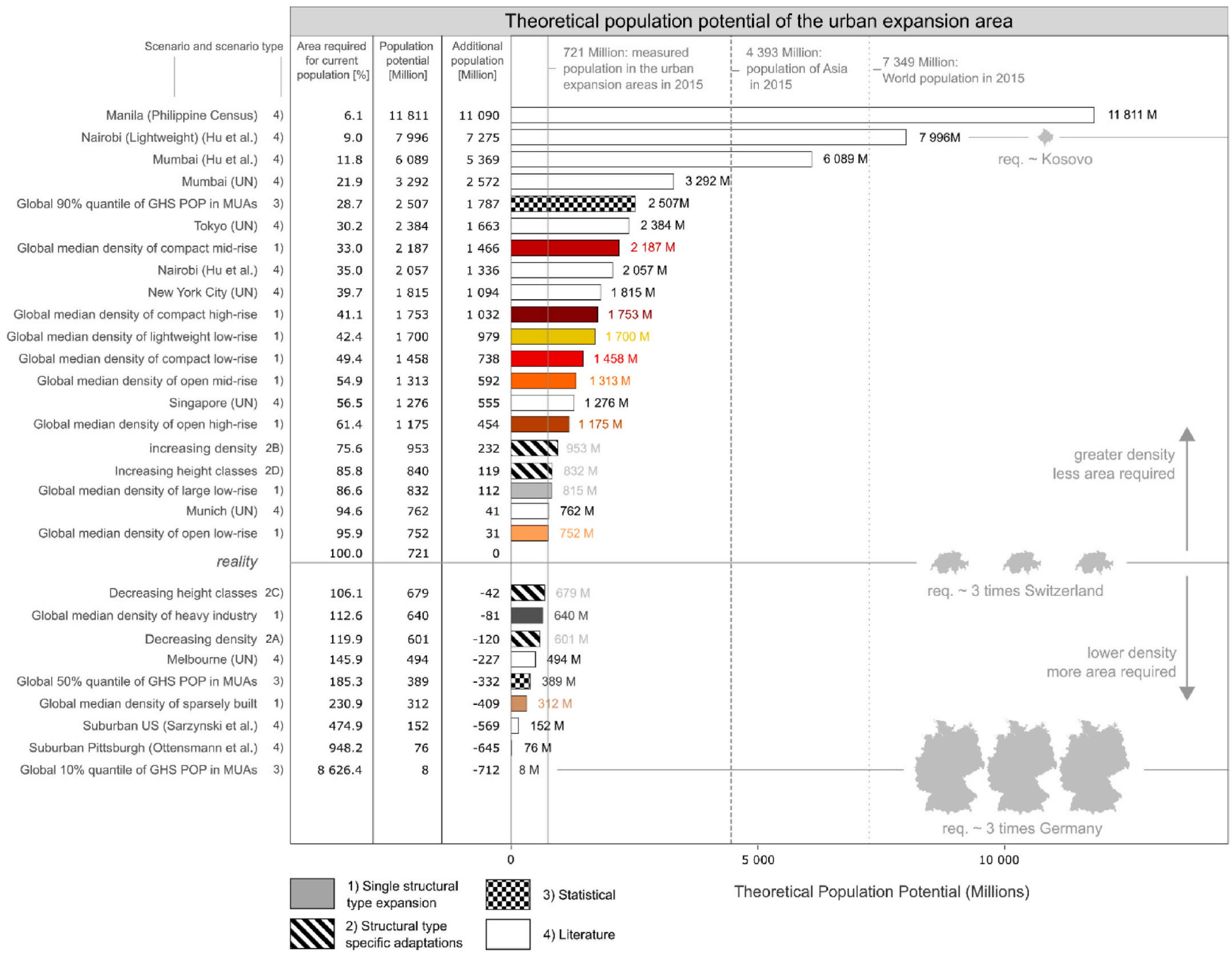

Fig. 7. Scenarios of theoretical carrying capacities of population for the expansion areas between 1985 and 2015. The scenarios refer to single structural type expansion (1), structural type specific adaptation (2 – A, B, C, D), to statistical models (3) and to literature-based models (4) (cf. section 4.3.).

reveal untapped potential. In Nairobi the population density of the 'lightweight low-rise' LCZ (LCZ-7), which is more or less equivalent to slums, is estimated by Hu et al. (2021) to be 48 241 inh/km^2. Extrapolated, this means that 7.996 billion people could live in these expansion areas if they were similarly densely populated. In other words: In addition to the 721 million people who actually live there, these areas could theoretically accommodate almost the entire current population of the world. Inversely, the urban expansion that took place between 1985 and 2015 that, as mentioned, in reality spans three times the area of Switzerland, could have been reduced to the consumption of only 10 842 km^2, i.e. about the size of only Hawaii or Kosovo, and still absorb the same population growth as it did in reality (Fig. 7).

Of course, it would also be possible to build less densely on urban expansion than was the case in reality. If urban expansion had taken place exclusively with 'sparsely built' LCZs (LCZ-9) in a *single structural type expansion* scenario, with a median population density of 1883 inh/km^2, then only 312 million people could live there, i.e. 409 million less than actually do. A *structural type specific adaptation* with a decrease in height (cf. Scenario D in Fig. 3), the carrying capacity would be lower by 42 million and with a decrease in density (cf. Scenario C in Fig. 3), the carrying capacity would be lower by 120 million, or required 19.9 % additional area. If it had been built and populated like the *statistical* bottom 10 % quantile across the globe, only 8 million people could live there. It would take, 1 142 282 km^2, i.e. about three times the extent of Germany, rather than three times the extent of Switzerland, to accommodate the measured population growth at this density (Fig. 7). To show one more *literature-based* extreme, if the newly constructed areas had been built and populated like the suburbs of Pittsburgh, with a density of 459 p/km^2 (Ottensmann, 2020), the area could only have housed 76 million people.

This gigantic range of scenarios shows how different built densities and population densities in cities are distributed across the globe and what big effects they have with respect to land consumption. Fig. 7 systematizes all these model calculations in relation to reality.

6. Discussion

In the monitoring period from 1985 until 2015, 32.9 % of the global population growth has taken place in the 1567 largest cities on our globe. However, urban land growth in the same period corresponded to only 19.5 % in relation to the global settlement area. This basically shows that urbanization in larger cities is generally space-saving. And although this could be seen as efficient, our analysis shows that the urban development was not ideal in terms of land consumption.

6.1. Urban expansion in structural and demographic low density

The main findings of this study are that in the 1567 largest cities across the globe with more than 300 000 inhabitants, urban expansion has been structurally less dense between 1985 and 2015 than the cities were on average in 1985. Thus, these cities widely have less dense structures in their entirety in 2015 than in 1985. In addition, the population densities in the newly built-up structures between 1985 and 2015 are substantially lower than in the older core areas. Of course, it must be also stated that population densities in these cities increased in general slightly. This testifies to an increase in the intensity of use in the urban core areas, which already existed in 1985, and these areas even compensate for the low population densities in the expansion areas.

It can therefore be said that structural urban expansion in terms of land consumption was unable to maintain the status quo of 1985 and was therefore not sustainable. The idea and call for more compact cities (e.g. by Glaeser, 2010; OECD, 2018; Angel et al., 2021) has thus not been realized, and, although population densities slightly increased overall in these cities, the expansion areas feature substantially lower population densities. It is therefore reasonable to conclude that new built structures need time to achieve population densities similar to those in central areas, even if the morphologic structure is comparable.

Our results are essentially in line with the results found by Angel et al. (2021) for a sample of 200 cities across the globe, by Siedentop and Fina (2012) for European cities and by Schmitt, Siedentop & Fina (2015) for post-socialist cities. Our study extends their findings by the number of cities, following the call of Bell and Jayne (2009) to redirect the distorting focus of research work on the largest cities on the globe to a more balanced analysis of smaller and larger cities. Furthermore, our study extends their findings with the intra-urban structural component as well as the consistent way of delineating cities. One consequence of this highly dynamic global urbanization (cf. Taubenböck et al., 2024) is that humankind is losing large amounts of fertile cropland and forest (van Vliet, 2019). So, if we do not succeed in developing new urban land more effective in terms of land consumption – which was until 2015 not the case – then we lose twice by losing productive agricultural land or forests without adequate compensation by providing housing to a larger amount of people.

Furthermore, we found that population densities in certain LCZs vary greatly around the world. This differs for LCZ type 'compact mid-rise' (LCZ-2), for example, between 28 000 inh./km^2 in South Asia to around 3000 inh./km^2 in North America. This shows, of course, that although the global statements in the first paragraph above reflect the basic trends, it is always necessary to differentiate between specific regions. And it shows that structural densification is an essential feature for achieving high population densities, but urban planning policies, cultural context, as well as other reasons can also lead to different densities in these structures.

With this study, we also follow the call of Hu et al. (2021), stating that intra-urban differentiation is necessary in multi-temporal city analyses. Our study here confirms what (Li, Verburg, & van Vliet, 2022) show in their study that population densities especially in Europe and North America and in parts of China are very low, and are therefore in global comparison not sustainable. Various effects play a role here, such as the growing demand for floor space area, especially in wealthier societies (Angel et al., 2021) translated into planning policies (Mangin, 2014; Monkkonen, 2019), the construction boom in China, which leads to so-called ghost towns or areas with a high underload (Shi et al., 2020), among other issues. The systematic analyses of local characteristics of cities against the here presented global trends opens up crucial future research directions.

Overall, however, it must be stated here that humankind is leaving a lot of potential on a global level in terms of structural and demographic urbanization. From the perspective of land consumption, urbanization must be developed more efficiently. And, of course, it is not just land consumption, but many other environmentally relevant variables which potentiate the negative consequences of low dense urban expansion: higher average gasoline usage, higher electricity usage or higher carbon emissions (Glaeser & Kahn, 2010; Iungman et al., 2024), to name just a few. This study aims to raise awareness of this potential. With this knowledge, we can perhaps answer the question more consciously as to whether we want to and can actively transform our ecologically damaged world, or whether we are being transformed by multidimensional developments.

6.2. The theoretical carrying capacity of urban expansion

From the main findings discussed above, one can conclude, we have a lot of potential to make urbanization more efficient in terms of land consumption. Our scenario calculations show the potential for saving space: If we would have built more densely, then we would have had great potential to accommodate many more people in the same urban expansion areas.

Assuming urban expansion with 'compact mid-rise' structures (LCZ-2) would allow 2.187 billion people to live there, i.e. an additional 1.466 billion people. In 2015 – the end point of our analysis – 3.86 billion people lived in urban areas worldwide. Using the above scenario, the world's largest 1567 cities alone could have absorbed the entire global urban population growth (to 4.7 billion United NationsDepartment of Economic and Social AffairsPopulation Division, 2018) by 2024 if they had been built more densely. This is not an entirely unrealistic scenario, nor would the population densities be so high that the quality of life would decline by definition. Many studies show that such structures can be developed with a high quality of life. Medium to high-density living has been shown to be acceptable to residents as long as these developments also provide at the same time an increase in quality green spaces, economically vibrant and mixed-use environments (e.g. Glaeser, 2010; Hollis, 2013; Sennett, 2018, p. 368).

Taking it a step further, our more extreme scenarios show the hypothetical potential of these expansion areas: With population densities such as in LCZ-7 proxying slums, almost the entire global population (7.99 billion) could live in these expansion areas. UN forecasts (United NationsDepartment of Economic and Social AffairsPopulation Division, 2018) up to 2050, however, only predict an increase of just under 3 billion new urban dwellers between 2015 and 2050. This means that the world's largest cities would not even have to be further built in such an admittedly extreme dense LCZ-7 way as to accommodate all future urban dwellers by 2050. However, this specific analysis in turn reveals the unimaginable population densities in slums (cf. Breuer et al., 2024) which goes along with terrible living conditions. Of course, one can argue that some densities we used for scenario calculations like those in Nairobi's slums are a high price to pay for saving space and that one would sacrifice one goal for another. But that's not the point in these theoretical experiments. These extremes are just to show how inefficient urbanization from the perspective of land consumption has actually been over the 30 years from 1985 to 2015. If we only look at the fact that built structures such as 'compact low-rise' (LCZ-3) or 'compact mid-rise' (LCZ-2) are estimated with the capability to accommodate an additional 738 million or 1466 million people – the latter number doubles the entire population of Europe in 2022 – then we are not talking about structures such as slums, which per se correspond to a low and over-dense type of low quality. Rather, these gigantic figures show that newly built urban areas have great potential in terms of space and therefore resource savings.

At the same time and in contrast, some densities, such as in American suburbs, show that this particular low-dense type of built-up structure is so land-consuming that if it would be the sole and prime structure type, only 152 million people could live in these new urban expansion areas. This low figure shows that certain forms of housing reflect an intrinsic excessiveness of modern societies embedded in the legal planning system (Mangin, 2014; Monkkonen, 2019).

Nevertheless, we do not want to sound naïve here and present the calculated potential that the same urbanized area would have as a realistic cipher. To be clear: not everything could be developed as efficiently in terms of land consumption as modelled here, nor would it be desirable. We need to be aware of how stable the built environment as well as practices, routines, building codes, planning ciphers or cultural expectations of building and living are and how difficult it is to change routines and attitudes (cf. Nassehi, 2024) even by implementing it into a legal apparatus (Tonkiss, 2013). It has to be said that while the theoretical experiments here show the potential of possible urban redevelopment, it is not possible to react collectively on a global scale. However, if this analysis demonstrates anything, it is that structural urban transformation is physically possible with denser structures that have already proven to be livable, suggesting that the demands of such transformation are not necessarily excessive.

To avoid a naïve perspective, it is important to acknowledge both the potential and the challenges of urban densification. Building denser cities offers a promising solution for accommodating the growing population (United NationsDepartment of Economic and Social AffairsPopulation Division, 2018) and increasing urban migration (Glaeser, 2010) while consuming less land. Defining these goals may seem straightforward, but the methods to achieve them—and their unintended consequences—add complexity. A sustainable strategy must consider multiple factors to prevent conflicting objectives from exacerbating issues such as the urban heat island effect, traffic congestion, and air pollution. Instead of relying on one-dimensional targets, urban density thresholds should be empirically identified to mitigate potential negative impacts.

6.3. Conceptual issues

From a conceptual perspective, there are also some issues that need to be considered: Unfortunately, no multi-temporal intra-urban structural classifications of the built landscape are available since 1985 at a global scale. Although some studies aim at intra-urban multitemporal analysis (e.g. Qi et al., 2024; Wang et al., 2019), they still focus only on a limited number of cities or single countries. The resolution of the satellite data in 1985 make intra-urban structural classification at the level e.g. of the here used LCZs challenging and it needs to remain open whether global multi-temporal data with sufficient accuracy for consistent multi-temporal analysis dating back to the 1980s will become available. Since built structures are comparatively long-lived and fundamental restructurings are generally rather rare or take place very slowly in consolidated urban tissues, we have assumed that the LCZs of today also correspond to the LCZs of 1985. We also assume that in the newly built urban areas, the LCZ type that we measure today has not changed over the course of the 30 years. It is therefore clear that this data-driven, conceptual simplification represents a certain distortion of the results. Of course, there are changes in the type of structure, which means we are neglecting an important component of urban development. However, we are unfortunately unable to quantify these intra-urban changes over time due to the current data situation. As these structural changes are, however, small in comparison to the dimensions of the data set, we assume that it does not have a significant statistical impact on the analyses.

Nevertheless, it is noticeable that the population densities in the same LCZs that already existed in 1985 are consistently higher than in the expansion areas. As this is systematically the case, we consider this trend to be plausible and assume that newly built areas need a certain amount of time to adjust to the corresponding densities. However, this can also be seen as an indication that structural re-densification has probably also taken place, which we cannot quantify with the current LCZ classifications. The quantity of these structural changes and related processes of densification and infilling or reduction of densities are due to availabilities of high-frequency and high-resolution data now possible and suggested for future studies.

6.4. Data and technical issues

From the *perspective of data*, there are some uncertainties that need to be discussed here: Every data set used in this study – whether the multi-temporal classification of urban expansion, the LCZs, the morphological urban areas or the population data – contains inaccuracies or even errors.

We can quantify the accuracies of the individual classifications, even if these are distributed very differently across the world. The WSF 2015 data set reports accuracies of 83–89 % (Kappa 0.55–0.78) (Marconcini et al., 2020), the LCZ classification have an overall accuracy of 87.3 % and a kappa value of 0.65, but with varying accuracies across the various LCZs (Zhu et al., 2022), the morphological urban areas are one consistent way of delineating cities allowing for true geographic comparisons, but they do not represent a universal urban-rural border (Taubenböck et al., 2019), and the GHSL population data set depends on the timeliness and quality of the census data and the accuracy of the building volume which was reported with an RSME of 2.40 m and 3.25 m, i.e. about one floor in general (Pesaresi, Corbane, Ren, & Edward, 2021). In addition, the input data has variable resolutions and projections and the harmonic integration leads to some intrinsic uncertainties (Johnson & Clarke, 2021). These, however, are minor and not quantified here since each data set has already been independently validated. Overall, we have not quantified which amplifying or attenuating combinations of inaccuracies lie in their combination. We suggest this issue to a separate study. It also makes sense to test the reliability of the results obtained from the data sets used here. This means that other current geodata are to be tested for each input data set – for example the GHSL (Pesaresi et al., 2015) instead of the WSF (Marconcini et al., 2018), the LCZ classification from Demuzere et al. (2022) instead of the one from Zhu et al. (2022), the WorldPop data (2025) instead of the GHSLPop (Schiavina et al., 2023) or the degree of urbanization (Dijkstra et al., 2021) instead of the MUAs (Taubenböck et al., 2019) for the city delineations, among other possible alternatives to our of current data. We suggest this also for a separate study.

In general, however, we can state that our input data have proven high accuracies and the achieved results are plausible. Denser and/or higher built-up LCZs indicate higher population densities and vice versa. The trends of the main findings, although variable across the globe, always point to the same direction which implies consistency and from a logical point of view also plausibility. For some data, we are particularly aware of inaccuracies. For the 'lightweight low-rise' LCZ (LCZ-7), as one example, that proxies slums, we are aware of the accuracy problems with population estimates, where underestimation is consistently documented (Abascal et al., 2024; Breuer et al., 2024; Taubenböck & Wurm, 2015). This makes it clear that although high population densities were measured in the LCZ class 'lightweight low-rise', these are certainly much higher in reality as informal populations are significantly underestimated in the census.

7. Conclusion

This study shows for the first time that urban expansion has made the world's largest cities between 1985 and 2015 less dense in terms of built-up structures. And, from a demographic perspective, the expansion areas feature significantly lower population densities than the older core areas. It can therefore be said that urban expansion was in terms of land consumption unable to maintain the status quo from 1985 and was therefore not particularly sustainable. This shows that urbanization can and perhaps must be made more efficient.

One can therefore argue in two directions: Even if the population densities in the urban expansion areas are low, one could argue that cities have become slightly denser overall and that this fulfils the call for more compact cities. Or, one could also argue much more ambitious that urban expansion has not utilized large parts of the potential for saving space which is generally attributed to it. We do have an incredibly high potential to more or less absorb the expected further urbanization trend with the existing areas through re-densification.

Every scientist, including us, must of course start from exactly the illusion that this new knowledge is a medium for ambitious urban transformation. At the same time, we must realize that we may not even have the control of urban-structural transformation in our hands, as the typically naïve sentence above – that this new knowledge is a medium for ambitious urban transformation – and that we all basically read in any conclusion to this topic should suggest. That means: we are aware that one can only develop what is controllable. This new knowledge on urbanization leads to insight, but not yet to targeted, realistic and realizable actions. Options for adaptations in the urban domain are not trivial. Too often, we natural or data scientists ignore the fact that societal conditions probably play the central role in any adaptation. With this in mind, we conclude this article with the call for inter- and transdisciplinary exchange to pass on this new knowledge to urban planners, politicians, and all other stakeholders taking knowledge into action – to work with ambition towards the goal of denser cities of high quality of life.

CRediT authorship contribution statement

H. Taubenböck: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **J. Mast:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **R. Lemoine Rodríguez:** Writing – review & editing, Conceptualization. **H. Debray:** Writing – review & editing, Conceptualization. **M. Wurm:** Writing – review & editing, Conceptualization. **C. Geiß:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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