RESEARCH ARTICLE

Rapid rise in urban sprawl: Global hotspots and trends since 1990

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Data Availability Statement: Our analysis relies on raw data from the Global Human Settlement Layer (GHSL) in four collection periods 1975, 1990, 2000 and 2014 distributed via the European Commission Science Hub (http://ghsl.jrc.ec.europa.eu/data.php). We used the Global Human Settlement built-up areas (GHS-BU; 38 m resolution; R2016A) and the GHS population grid (GHS-POP; 250 m resolution; R2015A), which are both available for all time periods. For the urban sprawl analysis at continental (n = 6 objects), regional (n = 23), national (n = 244), and subnational scales (n = 1,764), we used the Global Administrative Areas

Abstract

Dispersed low-density development–"urban sprawl"–has many detrimental environmental, economic, and social consequences. Sprawl leads to higher greenhouse-gas emissions and poses an increasing threat to the long-term availability of many vital ecosystem services. Therefore, urban sprawl is in stark contradiction to the principles of sustainable land use and to the need for a sustainability transformation. This study presents the degree of urban sprawl on the planet at multiple spatial scales (continents, UN regions, countries, subnational units, and a regular grid) for the period 1990–2014. Urban sprawl increased by 95% in 24 years, almost 4% per year, with built-up areas growing by almost 28 km^2 per day, or 1.16 km^2 per hour. The results demonstrate that Europe has been the most sprawled and also the most rapidly sprawling continent, by 51% since 1990. At the scale of UN regions, the highest relative increases in urban sprawl were observed in East Asia, Western Africa, and Southeast Asia. Urban sprawl per capita has been highest in Oceania and North America, exhibiting a minor decline since 1990, while it has been increasing rapidly in Europe, by almost 47% since 1990. The study revealed a strong relationship between urban sprawl and the level of human development as measured by the Human Development Index (*HDI*). The results suggest that it will be important for a more sustainable future to find a better balance between a high quality of life and using land more sparingly. There is an urgent need to stop urban sprawl, since current regulations and measures in developed countries are apparently not effective at limiting it. Monitoring urban sprawl can serve to guide policy development such as the implementation of targets and limits and to evaluate the effectiveness of urban growth management strategies at mitigating urban sprawl.

Author summary

In just 40 years between 1975 and 2014, humans converted more land to settlements than in all previous millennia combined, since they had started building the very first villages and towns. This is a dramatic acceleration. Dispersed expansion of settlements at low densities is called "urban sprawl". It has a number of detrimental environmental, economic, and social consequences. Using a globally consistent measurement method, we found that

dataset (GADM Version 3.6, 2018; https://gadm.org/data.html), which is freely available from a collaborative team from the University of California, Berkeley Museum of Vertebrate Zoology, the International Rice Research Institute, and the University of California, Davis. In addition, for analysis and visualization, we employed boundary data originating from the Natural Earth project (www.naturalearthdata.com). We used the Human Development Index for the year 2014 distributed by the Global Data Lab of the Institute for Management Research at Radboud University Nijmegen (https://globaldatalab.org/). As a global reference dataset on built-up areas, we used the Global Urban Footprint (GUF; https://www.dlr.de/guf) of 2016, which represents data collected in 2011/12, distributed for scientific use by the German Aerospace Center (DLR). In order to identify irreclaimable areas, we used a global land cover dataset called BaseVue 2013, which has been produced based on Landsat 8 imagery by MacDonald, Dettwiler and Associates Ltd. (MDA, British Columbia). The dataset has been used in previous human footprint studies and is accessible through ArcGIS online (https://www.esri.com/arcgis-blog/products/defense/defense/mdas-basevue-2013-global-land-cover-available-on-arcgis-online/).

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urban sprawl almost doubled between 1990 and 2014 across the globe, increasing by close to 4% per year. Europe is the most sprawled of the continents and exhibits the most rapid sprawl dynamics. In contrast, North America and Oceania show the highest values in terms of urban sprawl per capita. Urban sprawl also has increased significantly in fast-growing urbanized regions, particularly in coastal regions in China, West Africa, and India. Urban sprawl is strongly linked to the level of human development as measured by the Human Development Index. Much greater efforts are needed to use land more sparingly, especially in developed countries. This is an important issue of intergenerational justice because the built-up areas are passed on from one generation to the next. Accordingly, there is urgent need for action.

1 Introduction

Humans have taken up more land area for settlements in the 40 years between 1975 and 2014 than during all preceding centuries and millennia in history combined since the very first settlements were built on Earth [1]. Population growth and increasing urbanization have resulted in more than half of the global human population living in urban areas today [1]. These trends are poised to continue [2,3] and are addressed by several United Nations framework agreements that aim to provide guidance on how to best manage this growth, e.g., the Sustainable Development Goals (SDGs) and the New Urban Agenda [4,5].

Urbanization trends have kindled a diverse scientific debate about urban sprawl and urban compactness, which represent opposite types of urban development, and about the question of how sustainable or unsustainable they are [6–9]. The term "urban sprawl" refers to dispersed low-density urban development and applies to "the physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas" ([10] p. 6). Sprawl has also been described as an "excessive use of the open landscape by unsystematic, mostly weakly condensed extensions of settlement areas in the fringes of urban agglomerations" ([11] p. 119).

Urban sprawl results in the loss of open landscapes and wildlife habitats, degradation of important ecosystem services, and reduced resilience of ecosystems due to habitat fragmentation, wildlife population declines, and local extinctions [reviewed in 12–15]. It leads to the extraction of larger amounts of resources needed for construction such as sand, higher energy consumption, higher greenhouse-gas emissions, and increased traffic [12–15]. Higher expenditures for transportation infrastructure, electrical power, water supply, and wastewater collection are common consequences [12–15]. Urban sprawl has been strongly related to an unrestricted consumption of fossil fuels for transportation, heating, and service provision, loss of fertile farmland, and higher pressure on protected areas, and it exacerbates land-use conflicts [16]. Urban sprawl is caused by a combination of many factors [17–19] and has been discussed as a function of various drivers and geophysical contexts [20–22]. The drivers of urban sprawl include cultural, economic, demographic, and social ones [23], such as increases in property prices and individual lifestyle preferences for low-density, suburban living and home ownership, i.e., population growth is not the only driver. The expansion of built-up areas has also continued in many regions where the population is not growing anymore, and even in regions where the population has declined (e.g., East Germany, [24]). Some authors emphasized the relationships between patterns of urbanization, economic development, and various effects on society and the environment [25–27]. According to the Living Planet Report of 2014, countries of high level of human development have a particularly large ecological footprint ([28] p. 60). However, some countries of high human development may have a greater problem-solving capacity to mitigate urban sprawl and to evaluate the effectiveness of measures intended to reduce sprawl.

There are some positive effects of urban sprawl, e.g., that it responds to the wish of people for affordable single-family homes with a garden and more privacy [29]. However, increased competition for land often results in the intensification of agricultural production, the lack of land for renewable energy production, and higher pressure on protected areas [16]. Accordingly, greater competition for suitable land for food production, energy production, and urban development have been identified as the three central "ecological traps" that threaten humanity [16].

Because urban sprawl results from large numbers of individual actions and their effects, which cumulatively add up and persist into the future, it is an issue of intergenerational justice. Intergenerational environmental justice requires a fair approach to sharing resources across generations [30,31]. Because urban sprawl implies a cumulative alteration of the environment being passed on from generation to generation and has the potential to threaten the future, the current generation has a responsibility "to preserve that which is intergenerationally shared" ([31] p. 178). A turn-sharing approach to sustainability is proposed, which "encourages a generation to think of itself as a unity with collective responsibility" over their turn ([31] p. 178). Accordingly, avoiding the expansion of low-density urban areas into natural spaces helps maintain the benefits of these spaces (cleaner air and water, lower heat island effect, flood control, etc.) that the current generation inherited and can pass on to future generations.

To delineate hotspots of urban sprawl across the planet, to identify regional and global trends, and to assess the effectiveness of policies and other measures intended to limit or reduce urban sprawl, quantitative monitoring is required [12,13,32–34]. High-quality mapping of built-up areas is an important pre-requisite for effective environmental management for more sustainable patterns of development. However, comparisons of built-up areas between different points in time and different parts of the world are challenging due to differences in the definition of built-up areas, data availability, and technology applied for land-use mapping.

Earlier studies about urban sprawl mostly focused on particular urbanized areas, cities [35–38], countries [39], regions, or continents [13,40] for conceptual reasons or due to limited data availability. New global settlement datasets have recently opened up the possibility of global studies on urban sprawl [41]. The Global Human Settlement Layer (GHSL) by the Joint Research Centre (JRC) of the European Commission provides data on built-up areas covering four decades (1975, 1990, 2000, and 2014), which allows for an analysis of temporal changes in urban sprawl across the planet. Because urban sprawl affects landscapes at multiple scales and is not limited to cities and their immediate vicinity, this study investigates urban sprawl at multiple spatial scales to be able to compare fine-scale and coarse-scale spatial patterns, in contrast to many earlier studies of urban sprawl.

Accordingly, this study addresses the following questions: What is the extent of urban sprawl in reporting units at various spatial scales, namely continents, regions according to the UN Geoscheme [42], countries, subnational units (provinces, states, autonomous regions, etc.), and a regular grid (cell size of $50 \times 50\ km^2$)? How strongly has urban sprawl changed over time? What are the differences in urban sprawl dynamics between spatial units? How is urban sprawl related to the level of human development?

The focus is on the time period 1990–2014 because we anticipated that this period would reflect significant political changes such as the end of the Cold War in 1991, a major expansion of the European Union, and the rapid industrialization and urbanization in Eastern and South Eastern Asia, and Western Africa, with 2014 being the year of the most recent dataset available.

Three main hypotheses are examined: (H1) Agglomerations and coastal areas in particular are characterized by high urban sprawl values in the outskirts of many large cities and in regions of touristic development in coastal areas. (H2) Urban sprawl increased considerably on all continents, but most strongly in countries of strong urbanization trends (such as China, India, Western Africa, and Mexico). Increases in urban sprawl in European regions were expected to be less pronounced than in Northern American regions and much less pronounced than in East Asian regions. We anticipated that only a few regions would exhibit considerable decreases in sprawl. (H3) Urban sprawl would be strongly related to the level of human development, e.g., higher in Northern American and European regions than in less developed regions in Africa, Asia, and Latin America.

2 Materials and methods

2.1 Research approach

The research process started with the gathering of suitable global input datasets about built-up areas, inhabitants, land cover, boundaries of reporting units as well as socio-economic data (section 2.2). Several steps of data processing and analysis followed to measure urban sprawl at multiple spatial scales (section 2.3) and to examine the relationship between urban sprawl and human development (section 2.4). The validation of the results included an evaluation of the influence of the use of alternative settlement data and of the exclusion of specific land cover classes on the results at the national and sub-national levels (section 2.5). Fig 1 provides an overview of the research process.

2.2 Data Collection

This global study relies on raw data from the Global Human Settlement Layer (GHSL) [43–45] freely distributed by the EU Science Hub (https://ec.europa.eu/jrc/en). We used the Global Human Settlement Built-Up areas (GHS-BU, 38 m resolution) and the GHS population grid (GHS-POP, 250 m resolution). For the analysis at continental (n = 6 objects), regional (n = 23), national (n = 244), and subnational scales (n = 1,764), the Global Administrative Areas dataset [46] was used, which is freely available from a collaborative team at the University of California, Berkeley Museum of Vertebrate Zoology, the International Rice Research Institute, and the University of California, Davis. The number of national reporting units in the current study (n = 244) differs from the number of independent sovereign nations in the world (n = 193 in 2014), since autonomously governed parts of a patron nation such as overseas territories or provinces and several other entities with special legal statutes (e.g., Greenland, British Crown Dependencies, Overseas France) were considered as individual reporting units at the national scale (S10 Table). The analysis and visualization employed boundary data for the reporting units originating from the Natural Earth project [47]. To investigate the relation between urban sprawl and the level of human development, the Subnational HDI dataset from the Global Data Lab of the Institute for Management Research at Radboud University Nijmegen [48] was acquired.

In order to identify irreclaimable areas (unsuitable for construction), a global land cover dataset was used called MDA's BaseVue 2013 Global Land Cover, which was produced based on Landsat 8 imagery. The dataset has been used in previous human-footprint studies [49] and is accessible through ArcGIS online. To validate the 2014 results, the Global Urban Footprint (GUF, 12 m resolution) [50] was used, which also is a suitable global dataset. A complete overview of all input datasets is given in S1 Table.

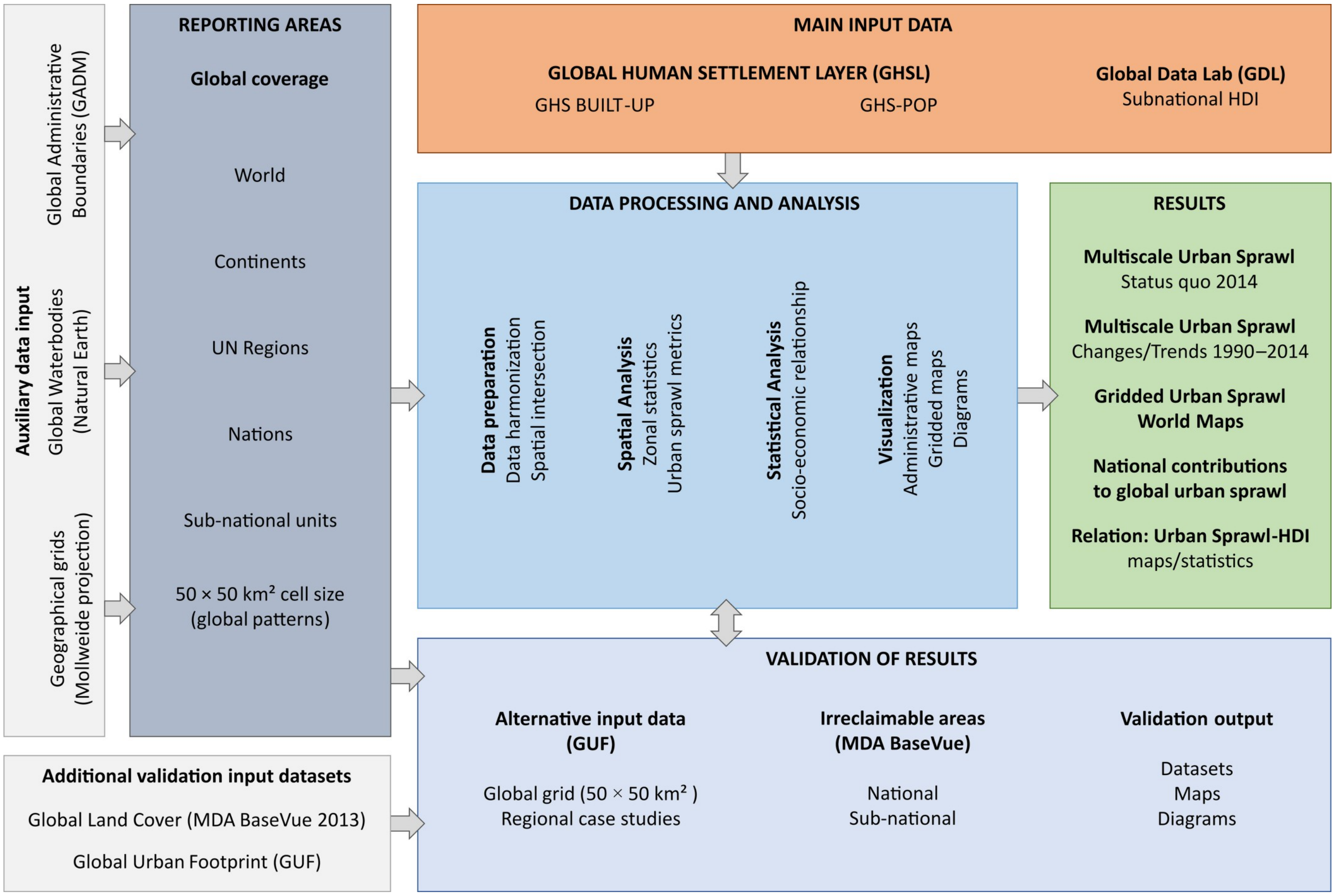

Fig 1. Overview of the research process used to measure the degree of urban sprawl on the planet at multiple spatial scales for the period 1990–2014. The colors indicate work packages related to main input data (orange), auxiliary and validation input data (light grey), reporting areas (dark grey), data processing and analysis (blue), validation (light blue), and results (green).

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2.3 Measures of urban sprawl

Existing approaches for measuring urban sprawl can be grouped in terms of complexity: (1) Use of many variables in parallel [51–53], (2) integration of many variables [54,55], (3) measures based on one or a few variables [38,56–59]. However, most definitions of urban sprawl proposed in the literature (reviewed in S1 Text, part A) consider three dimensions of urban sprawl: (1) proportion of built-up areas, (2) dispersion of built-up areas, and (3) low density [40]. All three dimensions are included in the metric of Weighted Urban Proliferation (WUP_p), measured in urban permeation units per square meter [UPU/m^2] (Fig 2; for a mathematical deduction see [60] and S1 Text, part B).

As a consequence, WUP_p measures a rather complex phenomenon in a relatively simple way. The consideration of the values of its three components along with the value of WUP_p is helpful for the interpretation of their combined value in WUP_p. Various tests of the behavior of WUP_p have shown that this method captures urban sprawl well [61] and, based on 13 suitability criteria for measures of urban sprawl [60], is more suitable than most approaches used previously. The method also satisfies the 34 requirements proposed in the literature for indicator selection for environmental reporting [62]. This method has been used in Switzerland by the Federal Office for the Environment [63] and in the latest study by the European Environment Agency (EEA) about urban sprawl in Europe [13,64]. The European study measured

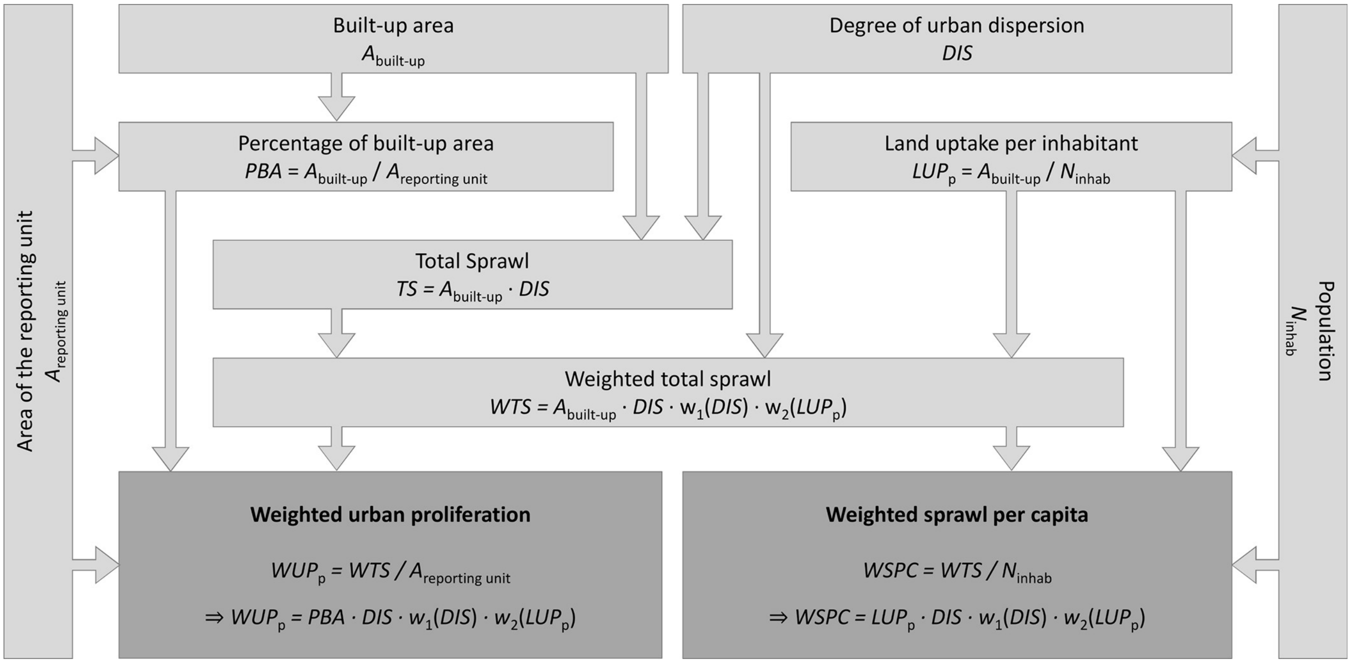

Fig 2. Overview of the two metrics of urban sprawl used in this study: Weighted Urban Proliferation (WUP_p) and Weighted Sprawl per Capita (*WSPC*) and their components. *PBA* = percentage of built-up area; *DIS* = dispersion of the built-up areas; LUP_p = land-uptake per person; N_{inhab} = number of inhabitants; $A_{built\text{-}up}$ = size of built-up area in the reporting unit; $A_{reporting\ unit}$ = area of the reporting unit (size of the landscape studied); *UP* = degree of urban permeation; *TS* = total sprawl; *WTS* = weighted total sprawl; w_1 and w_2 = weighting functions for *DIS* and LUP_p; see [60] for details.

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urban sprawl in 32 European countries at three spatial scales (countries, subnational regions, and 1×1 km^2 cells) for the years 2006 and 2009 [13].

To measure urban sprawl, the landscape-oriented metric of WUP_p [in UPU/m^2] was applied, along with a second metric to assess the average contribution to urban sprawl per inhabitant in each reporting unit (Weighted Sprawl per Capita, *WSPC*, unit: UPU/inhabitant). All calculations for each spatial scale were carried out separately on the basis of the raster layers of the GHSL dataset, i.e., a settlement mask and a population grid (for details see S1 Text, part C).

For the classification of urban sprawl values in maps, a rather small number of five classes was sufficient to capture the most important differences (based on the study by the European Environment Agency about urban sprawl in Europe [13] and expert opinion [65]) and worked well for all reporting units considered. WUP_p values < 0.1 UPU/m^2 indicate very low levels of sprawl; 0.1–0.5 UPU/m^2: low; 0.5–1.5 UPU/m^2: moderate; 1.5–3.0 UPU/m^2: high; and WUP_p values > 3.0 UPU/m^2: very high levels of sprawl. Based on inspected data distributions of *WSPC* values $< 3{,}000$ UPU/inhabitant indicate very low levels of sprawl per capita; 3,000–9,000 UPU/inhab.: low; 9,000–18,000 UPU/inhab.: moderate; 18,000–27,000 UPU/inhab.: high; and values $> 27{,}000$ UPU/inhab.: very high levels of sprawl per capita. Those reporting units that have a value of $WUP_p > 1.5$ UPU/m^2 and those that have a value of $WSPC > 18{,}000$ UPU/inhabitant are considered to be hotspots.

2.4 Investigating the relation between urban sprawl and human development

The Human Development Index (*HDI*) of 2014 served to capture the relationship between human development and the level of urban sprawl. The *HDI* is a measure that summarizes average achievement in three important dimensions of human development: a long and healthy life, being knowledgeable, and having a decent standard of living. It is quantified as the geometric mean of indicators of life expectancy at birth, average number of years of schooling, and gross national income per capita [66] and is available for subnational units. The current study applied the four classes of human development suggested by the Human Development Report [67]: low (less than 0.550), medium (0.55–0.699), high (0.7–0.799), very high (0.8 or greater). The analysis of the relation between urban sprawl and classes of *HDI* used contingency tables (S6 Table, S7 Table, S8 Table) and a Chi-square test [68].

2.5 Validation of urban sprawl findings

The Global Urban Footprint (GUF) of 2011 was considered as a suitable global dataset for validation of the results based on GHSL (S1 Text, parts D, E) for several reasons. The temporal and procedural efforts needed for an independent, quantitative evaluation of the GHSL dataset were not possible in this study. The data providers have already performed various quality assessments. The use of contemporary topographic maps to validate selected case studies for certain points in time (e.g., 1990) would be helpful, but would always be limited to national comparisons and the results would be difficult to generalize. At the global scale, to our best knowledge, no other comparable datasets exist in appropriate quality for the time before 2014 that would allow for an overall validation of the GHSL.

The measurement of urban sprawl can refer to reporting units including or excluding those parts of the landscape that are not suitable for the construction of houses or the establishment of settlements (so-called "irreclaimable areas") from the reporting units [64,65]. Both values have their respective valid meanings. Since landscapes differ in the amount of area that is not suitable for construction, a comparison of such landscapes may be more appropriately done after excluding the irreclaimable areas from the landscapes (S1 Text, part F). For example, the degree of sprawl of a reporting unit that includes glaciers may be compared more appropriately to a reporting unit without those areas after excluding glaciers. This means that the corresponding values of WUP_p then would provide the degree of urban sprawl of the landscape in relation to the area that is, in principle, potentially suitable for settlements. The values of *WSPC* are not affected because there are no buildings and no inhabitants in the excluded areas.

2.6 Strengths and limitations of the research approach

A very useful strength of the approach used here is the combination of the three components of sprawl into one landscape-oriented (WUP_p) and one inhabitant-oriented metric (*WSPC*). Earlier studies reported only single components of sprawl (e.g., built-up area), disregarded dispersion entirely or encountered difficulties with its quantification [69–71], intermingled several causes or consequences of sprawl [52], or integrated too many aspects of sprawl into a less transparent index [54].

Another strength is that the WUP_p-*WSPC* method can complement qualitative assessment methods of sprawl since qualitative aspects of urban sprawl may also be important and need to be considered in planning. The WUP_p-*WSPC* method is not intended to replace qualitative methods, but it can complement them and can thus enhance the tool-box of planners by providing quantitative assessments of planning alternatives (see section 4.7). One further strength is the applicability of the method at any scale. The larger the reporting units, the less variability is usually observed in the values, i.e., fewer extreme values, because the value of a group of reporting units combined can never be more extreme than the individual values of the reporting units [13]. Accordingly, the variability in values among UN regions is lower than among countries.

A limiting factor of the current study is that the GHSL dataset cannot be comprehensively validated. This study is based on the multi-temporal GHSL dataset and refers to the quality assessments already carried out by the data providers. Tests using several available reference datasets showed that the data quality of GHSL time series is better than other available global information layers from Earth Observation data [72]. Obviously, the reliability of the results depends on the reliability of the mapping of built-up areas based on satellite images. In some areas, the classified GHSL dataset includes motorways and some other large roads, which were impossible to remove from the dataset. While no single one dataset of settlement areas would address all potential issues of settlement analysis, a major advantage of the GHSL is its suitability for a temporal analysis of urban growth patterns for a period of 25 years (1990–2014) and, to some degree, even of 40 years (including 1975) [73]. Thus, this dataset can be considered to be highly appropriate for multi-temporal global urban sprawl analysis between 1990 and 2014. The present study also calculated sprawl metrics for 1975 to illustrate trends prior to 1990, but these results were not included in deeper analysis due to limited data comparability of the early remote sensing missions [73].

A final minor limitation is that this study used the formulas of the urban sprawl metrics regarding inhabitants only, where LUP_{p} is defined as land-uptake per person based on population data only (i.e., per inhabitant), while the original definition also included the number of workplaces. However, consistent data about workplaces are sometimes difficult to obtain, e.g., in multinational studies. Larger regions are comparable even without workplace data because the ratio between inhabitants and workplaces exhibits less variability among larger regions than among small reporting units, and issues due to the lack of workplace data become relevant only for small reporting units [13].

3 Results

3.1 Most recent state of urban sprawl (2014)

Large parts of the world are affected by urban sprawl at highly dissimilar levels (Fig 3, S2 Table, S3 Table, S4 Table, S5 Table). Contrary to initial expectations, urban sprawl at the continental scale in 2014 was higher in Europe than in North America (S1 Fig). Sprawl was much lower in Oceania, and lowest in Asia. Nevertheless, North America is the continent exhibiting the highest dispersion of the built-up areas, while land uptake per person was highest in Oceania (Fig 3 upper map, level of urban sprawl and its components).

Among the 23 UN regions, by far the highest level of sprawl was found in Western Europe, followed by Southern Europe, Northern Europe, Northern America, and Eastern Europe (S2 Table, S3 Table, S2 Fig).

The map of the national reporting units revealed highly disparate urban sprawl patterns (Fig 3 upper map). As expected, the highest values were found in several highly industrialized countries. Very highly sprawled countries in Europe comprise the Netherlands, Belgium, and Germany. Other major European countries with high urban sprawl values include the United Kingdom, Switzerland, Italy, Portugal, France, and the Czech Republic (S2 Table, S3 Table). Outside of Europe, highly sprawled countries include Japan, Puerto Rico, and Jamaica.

Examples of highly sprawled subnational units in Europe are many metropolitan areas (e.g., Hamburg, London, Prague, Lisbon, Zurich), South and North Holland (Netherlands), Antwerp and East Flanders (Belgium), North Rhine-Westphalia and Saarland (Germany), Campania (Italy), and Northwestern Switzerland (S4 Table, S5 Table, S3 Fig, S4 Fig). Among the 50 U.S. states, 19 exhibited high sprawl, mostly located on the east coast (e.g., Rhode Island, New Jersey, Connecticut, Massachusetts). Only seven states showed very low urban sprawl values (Alaska, Wyoming, Montana, North Dakota, Idaho, South Dakota, New Mexico). Subnational

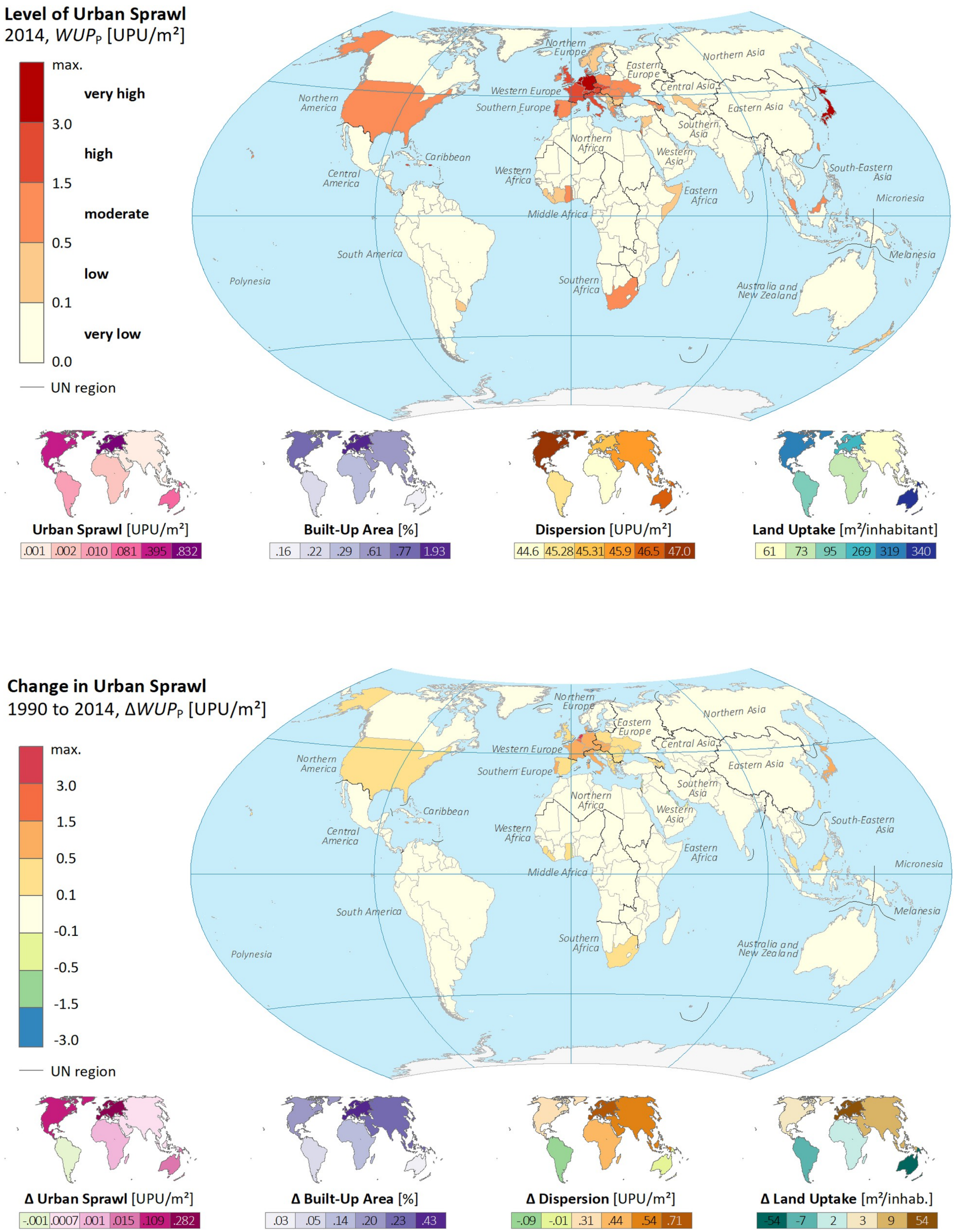

Fig 3. Level of urban sprawl in all countries and continents. Upper map: level of urban sprawl in 2014. Lower map: Changes in urban sprawl between 1990 and 2014. Data Source: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]

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reporting units outside the U.S. and Europe showing significant sprawl included Harare (Zimbabwe), Paramaribo (Suriname), Kuala Lumpur (Malaysia), Gauteng (South Africa), Greater Accra (Ghana), Nueva Esparta (Venezuela), the Metropolitan Area of Montevideo (Uruguay), and Toukai and North Kantō (Japan), among others (S4 Table, S5 Table).

3.2 Changes in urban sprawl 1990–2014

The global value of urban sprawl (i.e., of all land except Antarctica) increased by 95.2% in 24 years since 1990, corresponding to a yearly average increase by almost 4%. The built-up areas have grown by 45.6%, corresponding to 27.86 km^2 per day, or 1.16 km^2 per hour. Among continents, the strongest rise in urban sprawl was observed in Europe, followed by North America and Oceania. Europe is also the continent exhibiting the strongest increases in the components of urban sprawl (percentage and dispersion of built-up areas, land uptake per person) between 1990 and 2014 (Fig 3 lower map). A slight decrease in urban sprawl was observed in South America (S2 Table, S3 Table, S1 Fig).

At the national level, urban sprawl increased in two thirds of all countries between 1990 and 2014 (S2 Table, S3 Table, S4 Fig). The largest absolute increases in WUP_p were observed in the Netherlands, Belgium, Luxemburg, Portugal, and Germany. Among the fifty countries with the most substantial changes in WUP_p, Japan, Jamaica, Ghana, South Africa, Taiwan, and the United States were the most significant nations outside of Europe. China was among the countries (of a size > 100 km^2) showing the largest relative increases in urban sprawl, together with several East, West, and South African countries. India and Mexico were not among them.

At the subnational level, hotspots of high absolute increases in urban sprawl were found in South Holland (Netherlands), Antwerp Province (Belgium), the Lisbon metropolitan area (Portugal), Greater Accra (Ghana), Gauteng (South Africa), North Kantō (Japan), New Jersey (U.S.), North Rhine-Westphalia (Germany), Île-de-France (France), Massachusetts (U.S.), and Campania (Italy), among others (S4 Table, S5 Table). Hotspots of relative increases were located in Aragua (Venezuela), Centre-Nord and Plateau Central (Burkina Faso), Labe and Mamou (Guinea), Chongqing and Anhui (China), among others.

3.3 Relation between urban sprawl and human development

Most subnational units of high or very high urban sprawl exhibited high or very high *HDI*, whereas only 13.8% of all subnational units characterized by very low urban sprawl had a very high *HDI* (Fig 4). In contrast, regions of low or medium *HDI* rarely showed high or very high urban sprawl. About 21% of all subnational units were characterized by moderate to very high urban sprawl and high to very high *HDI*, e.g., parts of Germany, Japan, Belgium, the Netherlands, France, U.K., Italy, and the U.S. In contrast, about 40% were characterized by very low or low urban sprawl and low to medium *HDI* (e.g., subnational units in Southern Asia, Western, Middle, and Eastern Africa).

The results of the Chi-square test indicated a strong relationship and were highly significant ($\chi^2 = 484.03$, $p < 0.00001$) (S6 Table). Up to a certain level of human development (somewhere in the range between high and very high), urban sprawl was still limited (i.e., within classes very low to moderate), but above that level or transition zone, higher human development was strongly associated with very high urban sprawl, since in the very high *HDI* class, the moderate, high, and very high urban sprawl values were disproportionately high (S7 Table, S8 Table).

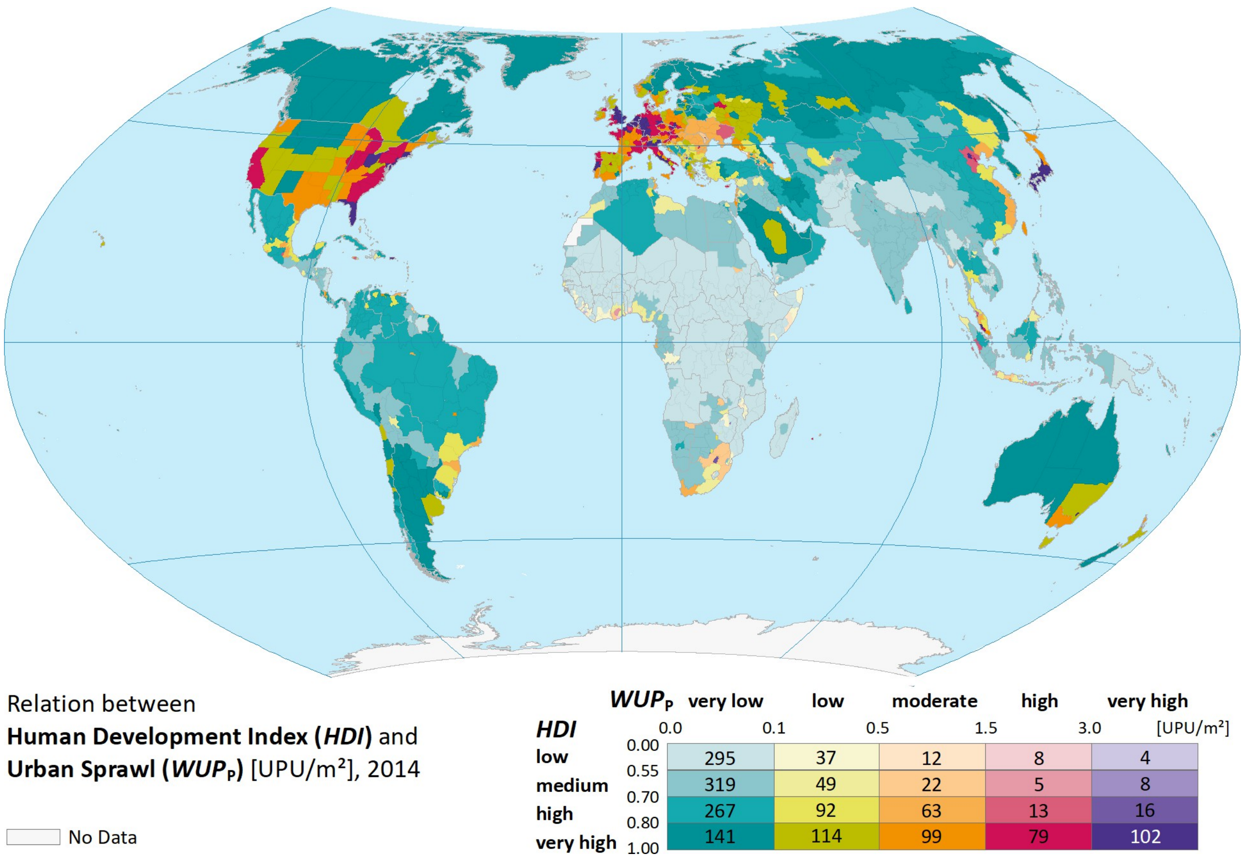

Fig 4. Relation between classes of human development (*HDI*) and classes of urban sprawl (*WUP*$_P$) at the level of subnational units. The colors represent combinations of classes of urban sprawl and human development. Numbers of units provided in the color legend, total = 1,745; 19 reporting units were not included due to missing data. Data Sources: Global Data Lab (GDL) @ Radboud University: https://globaldatalab.org/shdi/; European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds [1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Map made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Hammer Wagner. All map contents comply with PLOS license CC-BY 4.0.

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3.4 Patterns of urban sprawl in regular grids

To explore the patterns of sprawl in more detail, urban sprawl values are also presented for a regular grid (cell size of 50 × 50 km^2), based on the datasets mentioned above (19 m built-up mask, 250 m population grid, see S1 Text, part C). Many highly sprawled city regions are clearly visible in the upper map in Fig 5, for example, in the greater areas of Johannesburg, Mexico City, São Paulo, Moscow, and Tokyo, and in most of the megaregions in the U.S. (e.g., Great Lakes, Northeast, Florida, Gulf Coast, Southern and Northern California, Piedmont Atlantic, and Texas Triangle). Sprawl was also observed along many coastlines, e.g., the eastern coast of China (including Beijing, Tianjin and Shijiazhuang, the Shandong Mega region, and the HaiXia West Mega region), the coastal belt between Nigeria and Ghana, the western and parts of the eastern coastline of India, and several European coastlines (e.g., Iberian peninsula, French Riviera, and Atlantic coast).

Many river deltas and river courses were also affected, such as the Nile (Egypt), the Niger (Nigeria), Po (Italy), and the Yangtze River Delta (China). Sprawl was highly prevalent on Java Island (Indonesia), Honshu Island (Japan), and the Caribbean Islands. Australia's city regions of Melbourne, Adelaide, Perth, Sydney, and Brisbane were strongly affected as well.

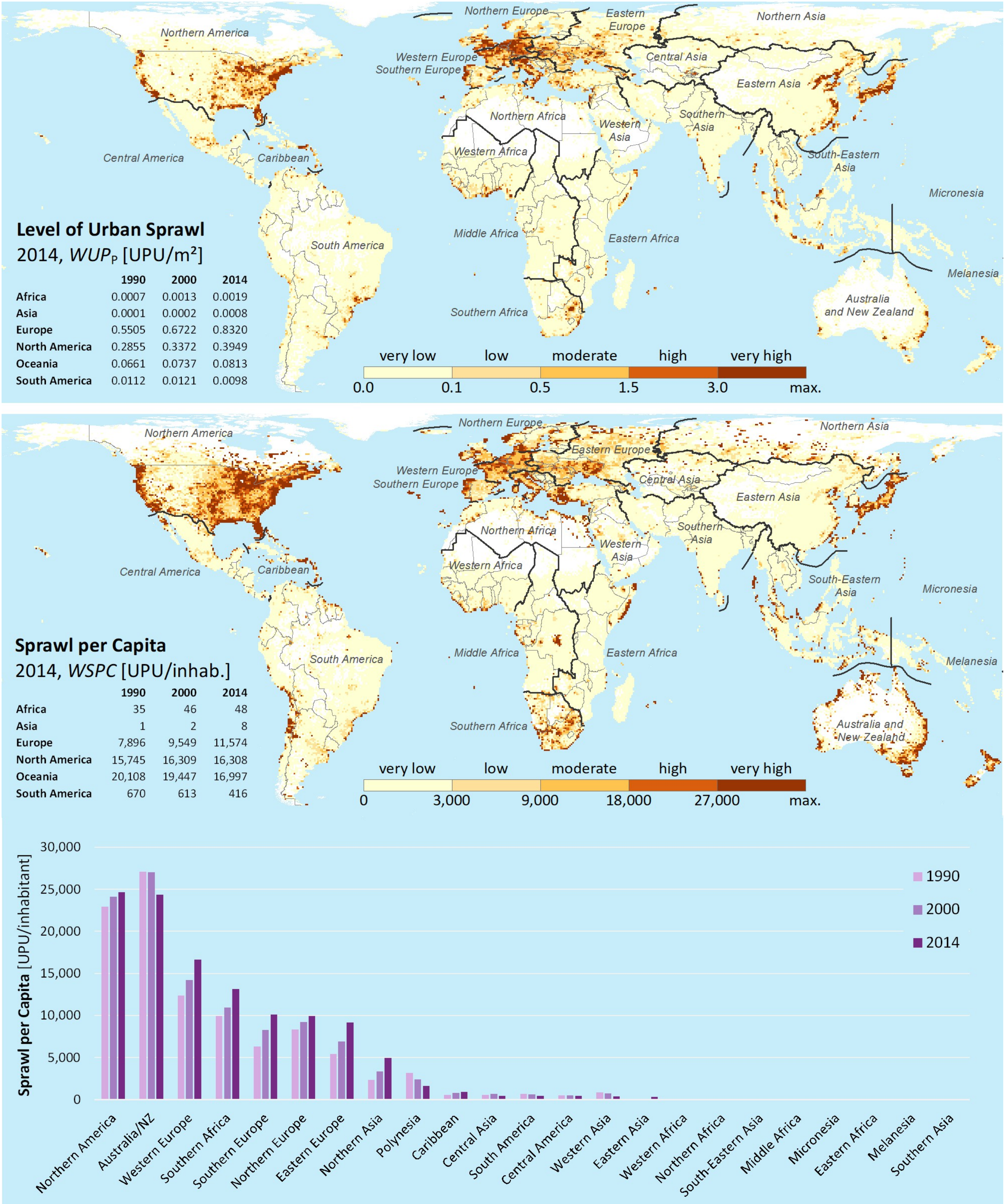

Fig 5. Global distribution of urban sprawl and weighted sprawl per capita in 2014 at the scale of a 50 × 50 km^2 grid. The tables indicate the values of the six continents in 1990, 2000, and 2014. At the bottom of the figure, the values of the *WSPC* in the UN regions are shown in bar charts. The UN regions are indicated by black lines. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Map made with Natural Earth and GADM:

Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Behrmann. All map contents comply with PLOS license CC-BY 4.0.

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The comparison of absolute and relative changes in urban sprawl and urban sprawl per capita revealed that the comparatively low relative changes in Europe and North America represent dramatic absolute increases considering the high level of urban sprawl already present in the past (S5 Fig, S6 Fig). Accordingly, the largest absolute changes were found here (in both metrics), while regions that do not have such a high level of urban sprawl were characterized by important relative increases. China exhibited pronounced high to very high relative changes in urban sprawl, followed by Russia, Brazil, India, and Indonesia. Countries from Western Africa (e.g., Nigeria) and Central America (Mexico) also showed significant relative increases in both metrics. High relative increases were seen particularly in many Chinese provinces (Inner Mongolia, Xinjiang, Guangxi, Qinghai, Hunan, Shandong, Yunnan), in India (Rajastan and Maharashtra), in Nigeria (North West. North Central) as well as in Kazakhstan (North and West Region) and Australia (Western Australia, Northern Territory).

At the scale of a 50 × 50 km^2 grid, cells of high to very high urban sprawl ($WUP_p > 1.5$ UPU/m^2) were present in 130 national units in 2014. Overall, the total number of these cells was 2,099 (Fig 6, upper left diagram). The U.S. accounted for the largest proportion (25%) of cells of high to very high urban sprawl on the globe, followed by China (8%). In several other cases, the number of cells with high urban sprawl values per country was almost independent of country size: France, Germany, and Japan showed proportions of 5 to 6%. Russia, Italy, and the United Kingdom were also among the top 10 countries contributing to global sprawl.

The total number of cells with a high or very high increase in urban sprawl ($\Delta WUP_p > +1.5$ UPU/m^2) in the period 1990–2014 was 763 (Fig 6, upper central diagram). In 77 of all 244 countries, cells with a high or very high increase in urban sprawl were present. The main contributing countries were the U.S. (27%), China (16%), Japan (5%), South Africa (4%), Italy (4%), France (4%), and Indonesia (3%).

In contrast, the total number of cells with high or very high decrease in urban sprawl ($\Delta WUP_p <$ -1.5 UPU/m^2) was only 72, distributed within 37 countries. Among them were several developing and emerging countries such as Indonesia, Venezuela, Brazil, Thailand, Iran, Argentina, Vietnam, and also China and Japan (Fig 6, upper right diagram).

3.5 Patterns of Weighted Sprawl per Capita

The values of Weighted Sprawl per Capita (*WSPC*) address the question of how much, on average, inhabitants contribute to urban sprawl. The results for the regular grid (50 × 50 km^2) revealed large areas of high values on all continents (second map in Fig 5). Most hotspots of *WSPC* were located in Europe and Northern America, but some were in Japan, Southern Africa, in coastal areas of Australia, New Zealand, and along the Pacific coast of South America. Numerous urban regions in developing countries showed elevated values as well, e.g., Rio de Janeiro and Buenos Aires. Among the UN regions, Northern America and Australia/New Zealand exhibited by far the highest *WSPC* values (bar chart in Fig 5), followed by the four European regions, Southern Africa, and Northern Asia (which was considered as a separate region).

The national contributions at the scale of the 50 × 50 km^2 grid to the level (2014) and the changes (1990–2014) in global *WSPC* are summarized in Fig 6 (bottom row). The country contributing most strongly to the level of *WSPC* was the U.S. (37%), whereas Russia (21%) contributed most to the increases in *WSPC*, followed by Australia (16%), the U.S. (13%), and

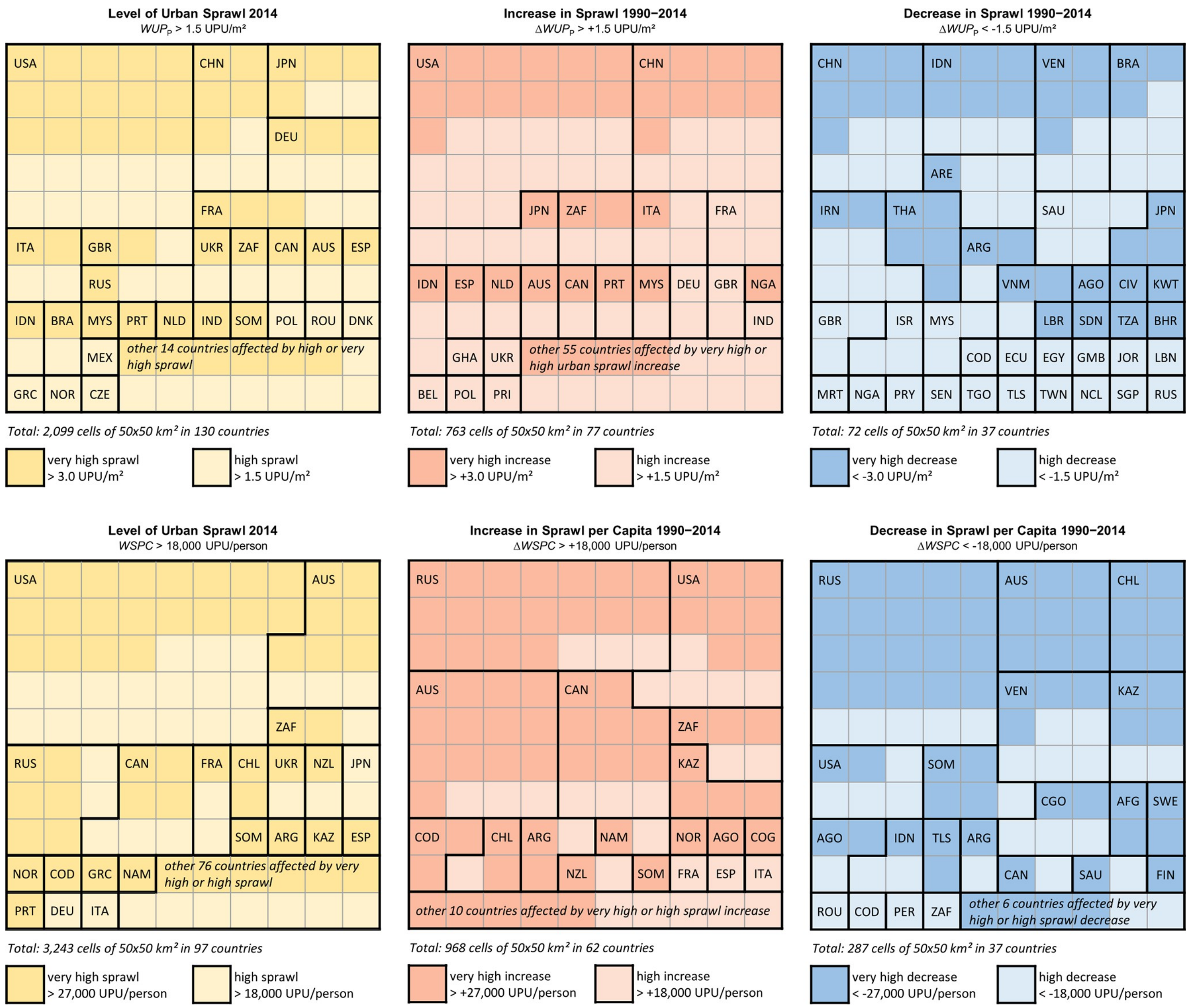

Fig 6. National contributions to urban sprawl (2014), weighted sprawl per capita (2014), and to the respective changes (1990–2014) at the scale of a global 50 × 50 km² grid. Each rectangular diagram of 10 × 10 squares represents the global amount of cells that were classified as high or very high urban sprawl or as high/very high increase or decrease in sprawl, respectively, i.e., each square represents about 1 percent of sprawled areas globally. The national contributions to global urban sprawl were grouped together as indicated by black boundaries. The shades of lighter and darker colors distinguish between high and very high urban sprawl values. Country names are indicated by their ISO 3166 country codes (see complete list in S10 Table). Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.

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Canada (11%) showing large proportions. Russia (25%) also showed the highest proportion of cells with decreasing *WSPC* values, followed by Australia (9%) and Venezuela (9%).

3.6 Global trends in urban sprawl

Regarding major global trends, Europe showed the strongest increases in both landscape-oriented (WUP_p) and inhabitant-oriented measures (*WSPC*) of urban sprawl between 1990 and 2014 (Fig 7, small tables in Fig 5). Europe's value of WUP_p increased by 51.1%, while WUP_p increased by 38.3% in North America. The absolute increase in Europe's value of WUP_p

(0.2815 UPU/m^2) is 2.6 times that of North America (0.1094 UPU/m^2). Relative to the U.S. as the main contributor to sprawl in North America, Europe's value of WUP_p increased from 84.7% to 93.4% of the corresponding value in the U.S. between 1990 and 2014 (S2 Table). In contrast, the value of *WSPC* in 2014 still was considerably higher in Oceania and North America than in Europe. However, Europe exhibited a dramatic increase by 46.6% since 1990, whereas the values in Oceania and North America decreased moderately (by 16% and 14%, respectively). Their values were all very high compared to the other continents, even though the entire Asian continent showed an eightfold increase in its *WSPC* value.

The intensive urbanization processes in Asia and Africa were reflected in very high relative increases in urban sprawl and urban sprawl per capita (S5 Fig, S6 Fig). For example, Eastern Asia (+1,583%), South-Eastern Asia (+667%), and Western Africa (+601%) showed the highest relative increases.

3.7 Influence of alternative settlement data and irreclaimable areas on urban sprawl findings

In addition to the results presented above, urban sprawl values were also calculated based on the GUF, which roughly corresponds in time to the GHSL layer for 2014 (S7 Fig, S8 Fig, S9 Fig, S10 Fig). The values of urban sprawl metrics were in very high agreement between the two data sources both at the planetary scale and at a more detailed scale at which five case studies (S11 Fig, S12 Fig, S13 Fig, S14 Fig, S15 Fig) were examined using a grid of 5 × 5 km^2 cell size (S1 Text, parts D, E).

Relevant irreclaimable areas were determined for all reporting units using the high resolution MDA's BaseVue 2013 Global Land Cover dataset [49] to assess their influence on the values of WUP_p. Apart from a few reporting units at the national and sub-national scale, no major changes in the values that would question the general findings and conclusions of this study were observed (S1 Text, part F, S16 Fig). However, a comprehensive identification of all irreclaimable areas can be challenging at the global scale because of limited data availability and because protection regulations differ considerably among countries.

4 Discussion

Using the GHSL data, this study measured urban sprawl on the planet at five spatial scales over a period of 24 years and examined its relationship with the level of human development. The findings are based on a measurement approach applied uniformly across the planet. The following sections discuss the results to address the three hypotheses about the extent and the changes in urban sprawl at multiple scales and the relationship between urban sprawl and the level of human development. The final sections elaborate on the need for explanatory models and for measures to mitigate urban sprawl.

4.1 Extent of urban sprawl at multiple scales

The current empirical findings confirm the first hypothesis of this study for many parts of the world: The results identified a number of urban and suburban regions with high levels of urban sprawl on all continents (Section 3.1, Fig 3 upper map, S1 Fig, S2 Fig, S3 Fig, S4 Fig, S2 Table, S3 Table, S4 Table, S5 Table). High urban sprawl in agglomerations can, in many cases, be explained by high dispersion and low density on the outskirts of large cities [38]. Moscow and Montréal are presented as illustrative examples in S17 Fig and S18 Fig. In Europe, the so-called "Blue Banana" region [74], discussed in the literature as an urban industrial and service corridor with about 111 million inhabitants, forms a large area of high sprawl from Northern

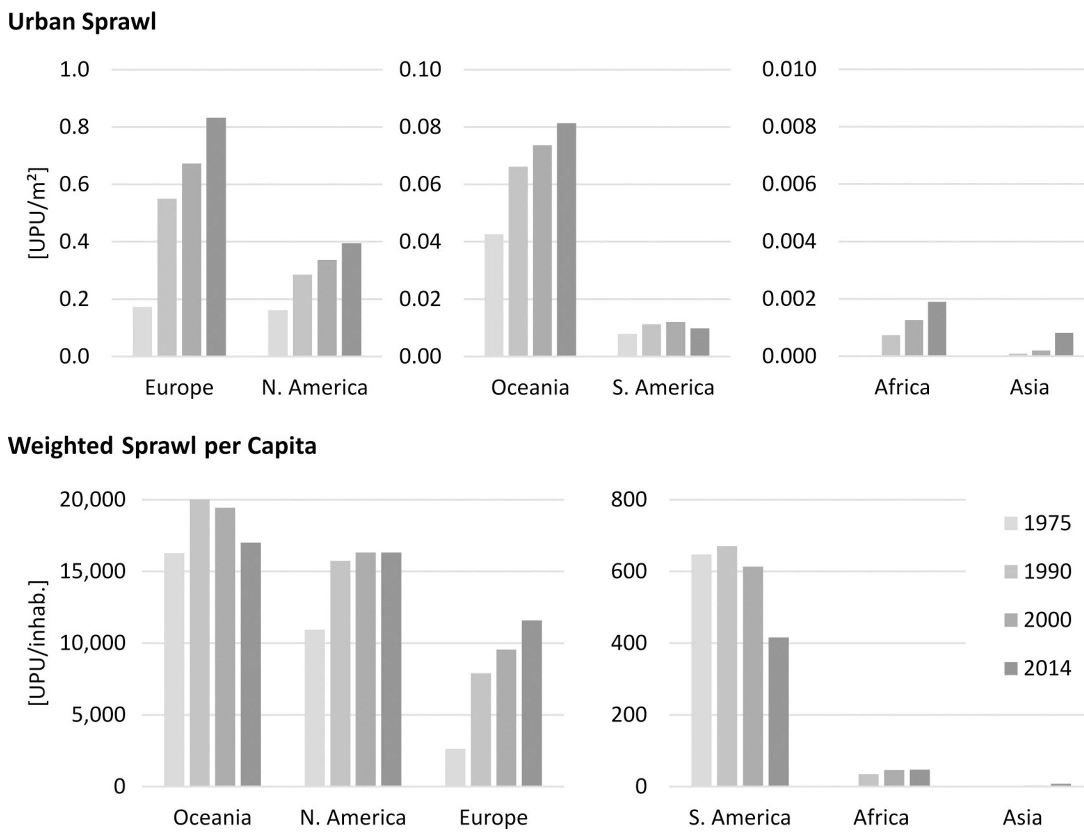

Fig 7. Development of urban sprawl (WUP_p) and urban sprawl per capita ($WSPC$) between 1975 and 2014 at the scale of continents. The values of 1975 were included here for comparison, but they were not evaluated in more detail. An extended version of this figure that includes the three components of sprawl is presented in S1 Fig. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.

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Italy, through Germany and the Netherlands, and across the North Sea to the North of England (S19 Fig).

In coastal regions that are attractive for tourism, many characteristic examples of urban sprawl were found at the levels of 50 × 50 km^2 and 1 × 1 km^2 grid cells. Illustrations of such areas along coastlines are provided in S20 Fig and S21 Fig using Los Angeles and the French Riviera.

Strano et al. [41] emphasized that the abundance of low-density areas covering about 50% of the global terrestrial surface requires greater attention from the scientific community. Using the method of WUP_p and $WSPC$, the current results help address this need by identifying urban sprawl patterns at multiple scales for several points in time. The results from the five spatial scales are in good agreement and reveal more detailed information at increasingly finer scales. No contrasting patterns or trends in urban sprawl were observed between different scales.

4.2 Differences in urban sprawl dynamics between reporting units

The second hypothesis was not confirmed in its generality, especially the expectation that increases in urban sprawl would be less pronounced in European regions than in Northern American regions and much less pronounced than in East Asian regions. Despite strong ongoing urbanization processes in South Eastern Asia and Western Africa, the most significant increases in urban sprawl were still observed in Europe and in the U.S. (Section 3.2, Fig 3 lower map, S1 Fig, S2 Fig, S3 Fig).

The contrast between non-sprawling and sprawling regions was even more dramatic when considering the metric of urban sprawl per capita (Sections 3.5, 3.6, Fig 5, S5 Fig, S6 Fig): Northern America, Australia, and Europe showed by far the highest values compared to all other regions. While at the sub-national level and at the 50 × 50 km^2 grid level, significant increases were observed in some of the fast-growing urbanised regions (e.g., coastal regions of China, West Africa, and India), most cells of 50 × 50 km^2 with high or very high increases in urban sprawl were located in Northern America, Eastern Asia, and Western Europe (Section 3.4, Fig 6). Although decreases in urban sprawl were observed in a few regions, it is by no means possible to speak of a trend reversal toward using land more sparingly.

The current findings about relative changes in urban sprawl are in close agreement with previous studies of urban expansion indicating that regions in Asia, Africa, and South America showed the highest growth rates between 1970 and 2000 and were also among the predicted growth regions in future scenarios [3,75,76]. In addition, the results demonstrate that Europe and North America still experienced the highest absolute changes in urban sprawl.

It seemed difficult for earlier studies of urban sprawl that were based on a subset of cities or other urbanised areas to distinguish clear patterns between different countries and continents. Gerten et al. [37] argued that the consolidation phase of urban areas in Europe began earlier and cities were more mature and less dynamic in their development compared to those in other regions of the world. They stated that their analysis of 600 cities by continent did not reveal clear differences in interpretation at different points in time between 1975 and 2014. A recent study by the Organisation for Economic Co-operation and Development (OECD) about urban sprawl in 1,156 urban areas from 29 OECD countries arrived at a similar conclusion that many cities and countries experienced a process of urban sprawl since 1990, but the manifestations were very heterogeneous [38]. To reveal global trends, a global study like the one presented here is needed.

4.3 Relation between urban sprawl and the level of human development

One of the most striking findings of the present study was that high levels of urban sprawl were most evident in the most highly developed countries (Section 3.3, Fig 4, S6 Table, S7 Table, S8 Table). There seems to exist a transition zone that characterizes the transformation of landscapes by urban sprawl when a certain level of human development is surpassed. According to the presented results, this transition zone seems to be of particular importance for monitoring and mitigating urban sprawl in the future. While the statistical results at the scale of subnational units do not provide clear evidence of causality and various other variables may have an influence on this relationship as well, they indicate a strong association between urban sprawl and the level of human development.

The current results showed that 30% of all OECD countries were affected by high levels of urban sprawl (WUP_p) and almost 90% were affected by high levels of urban sprawl per capita (*WSPC*). Most of them have established sophisticated planning systems long ago, such as the Netherlands, often referred to as a "planner's paradise" [77], but urban sprawl has clearly not been addressed sufficiently by planning regulations. Rather, they might even–perhaps unintentionally–stimulate sprawl through oversized designated building zones [78] and by supporting the construction of residential and commercial areas at low density [38]. For example, many zoning codes mandate certain requirements such as significant front-yard setbacks pushing buildings back from the street, compliance with maximum densities, minimum street widths, and zones for single family homes. Such restrictive zoning codes contribute to an increase in urban sprawl and make it very difficult to implement measures that could slow it down.

4.4 Need for explanatory models of patterns of urban sprawl and for comparative studies of alternative future scenarios

Global patterns of urban sprawl will need to be better understood in their respective context of legal and socio-economic conditions, planning regulations, and planning practices. Explanatory models of drivers of urban sprawl and their relative importance can serve this purpose in the future [79]. They can consider multiple scales to analyze spatial characteristics such as the morphology of towns and cities and their growth patterns, building cultures, architectural traditions, and geographical conditions (e.g., elevation, soil quality) and to develop appropriate approaches for sustainability interventions. A multitude of potential drivers will need to be considered including future population growth, such as differences in property prices [6,80], changes in economic opportunities, and increased options for working remotely, which may contribute to accelerated suburban and rural development [81,82], but also energy prices, increasing awareness of the relation between urban sprawl and intergenerational justice, and changes in residential preferences.

The global results presented here provide many opportunities for comparative studies, for example, in terms of future scenarios of global urban expansion [2,75,76,83] and increased road construction [84], also in relation to the global map of remaining roadless areas [85], and for developing an "Urban science for global sustainability" [86,87]. Modeling the effectiveness of urban growth management strategies and identifying more sustainable urban development scenarios will be crucial to assess scenarios that allow for the maintenance of a just livelihood for all human beings and avoid further aggravation of land-use conflicts and biodiversity loss [2,16].

4.5 Measures to mitigate urban sprawl

Because each city and each urbanizing region has its unique characteristics due to its geography and socio-economic and cultural history, each can benefit from a particular mix of land-use strategies specifically tailored to its conditions. Much higher efforts will be required to reduce the ecological footprints of cities, particularly in developed countries, and to improve quality of life in developing countries according to Sustainable Development Goal (SDG) 11 ("*Make cities inclusive*, *safe*, *resilient and sustainable*"). According to Abson et al. ([88] p. 30), future sustainability efforts will "need to focus on less obvious but potentially far more powerful areas of interventions" and corresponding "leverage points" should be identified. A global monitoring framework for SDG 11 may be helpful for this task by including data about urban sprawl and would enable actors to make more informed decisions about future urban growth management strategies and to assess their performance. The UN World Cities Report is an important discussion forum of sustainable urbanization [89]. It would also benefit from integrating urban sprawl metrics to assess and compare various settlement patterns. Wolfram et al. ([90] p. 444) emphasized that improved urban planning is crucial to strengthen the transformative capacities of cities. From a methodological perspective, the WUP_{p}-$WSPC$ method can improve the toolset of planners, because it enables planners to better predict future levels of sprawl for a suite of planning scenarios, to establish environmental standards (targets and limits), and to evaluate the effectiveness of measures intended to mitigate sprawl [34]. Planners can compare and adjust the extent, spatial location, and density of new designated building zones to minimize their contribution to sprawl. Existing building zones that have not yet been built over can be de-zoned when their use would contribute to urban sprawl [78]. A central issue of concern is how power can be redistributed among the different levels of government. Currently, many municipal authorities rely on land development to maintain and increase their tax base.

Examples have demonstrated that sprawl can be reduced through measures such as brownfield recycling (re-use or redevelopment of abandoned or derelict areas) and better cooperation among municipalities for large-scale planning to minimize the number and size of commercial and residential areas [13]. De-sprawling strategies to use land more sparingly and to find a better balance between increased urban density, attractive and human-oriented architecture, and sufficient green space are of particular importance [64]. Greenbelts and the densification of existing built-up areas can also help keep green spaces from being built over [91–93]. Land-use plans need to be examined in terms of their contribution to urban sprawl [34], while public awareness of the negative impacts of urban sprawl must be enhanced swiftly. Densification plans need to consider and avoid or mitigate as much as possible negative consequences of high urban density. This can be achieved by combining increased density with high-quality architecture and design, avoiding overly high densities, and good judgement that balances density with diversity, mixed-use development, sustainable transportation (e.g., shift to public transport and bikepaths and transit-oriented development), and the protection of urban green spaces [13,94]. Aspects of urban climate have to be addressed by safeguarding urban parks for recreation and fresh air production and avoiding urban heat islands [38,94,95]. The concept of the "15-Minute City", in which everything that residents may need (stores, restaurants, etc.) is accessible by walking or cycling within 15 minutes, is also supportive of compact urban development and has been discussed in relation to a net-zero urban future [96]. These can all contribute to a fair turn-sharing approach to sustainability [31].

Learning from successful examples can inspire planners and decision makers and can help avoid repeating common mistakes [78]. For example, in Switzerland, as a consequence of intense public debate, the Swiss Spatial Planning Act was revised in 2013 to make urban development planning regulations stricter. Banks can also make important contributions to control sprawl. For example, the Banque Alternative Suisse (BAS) does not give mortgages anymore to projects that would strongly contribute to urban sprawl [97]. They have informed the public about their approach in press releases and on their website to attract new customers who want to invest in an ethically responsible way.

5 Conclusion

Using new satellite image data, this study identified hotspots and trends of urban sprawl at multiple spatial scales and for three points in time to serve as a basis for an evidence-based debate about global urban sprawl and its consequences, to identify changes in trends, and to evaluate the effectiveness of measures intended to reduce sprawl. High levels of urban sprawl in many regions of the planet and rapid increases between 1990 and 2014 paint a concerning picture of unsustainable development. The strong association between human development and urban sprawl implies that a more sustainable future will require a better balance between quality of life and urban development patterns. It is a remarkable irony in human development of recent decades that the more knowledge and planning capacity societies have at their disposal, the more common has been the emergence of high urban sprawl.

Further increases in sprawl can be avoided if appropriate regulations and incentives are created. Long-term strategies are required such as major improvements of public transport and a reduction of car dependency, rather than further expansion of low-density urban areas on the outskirts. According to projected population growth, urbanization trends, and massive increases in road construction, urban sprawl in many parts of the planet will continue to increase rapidly and will result in growing negative effects that are typical of unsustainable development unless rigorous efforts are made for a transition toward a trend reversal.

Supporting information

S1 Fig. Development of urban sprawl metrics between 1975 and 2014 at the continental scale. The diagrams are based on all available GHSL time series. 1975 values have been calculated and integrated for presentation completeness, but have not been included in the deeper analysis due to data validity reasons of early remote sensing missions. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
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S2 Fig. Development of urban sprawl between 1975 and 2014 at the scale of sub-continental regions (UN regions). The diagrams are based on all available GHSL time series. 1975 values have been calculated and integrated for presentation completeness. UN Region Eastern Europe was split here into "Eastern Europe" and "Northern Asia" (Asian part of Russia). Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
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S3 Fig. Development of urban sprawl between 1975 and 2014 in large (population $>$ 5 million, area $>$ 20,000 km^2) countries and subnational units with high and very high urban sprawl values ($WUP_p > 1.5$ UPU/m^2 in 2014). The diagrams are based on all available GHSL time series. 1975 values have been calculated and integrated for presentation completeness, but have not been included in the deeper analysis due to data validity reasons of early remote sensing missions. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
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S4 Fig. Dimensions of urban sprawl metrics of national and subnational units in 2014 (Filter: $POP > 5$ million, $Area_{admin} > 20{,}000$ km^2, $WUP_p \geq 1.5$ UPU/m^2). For subnational units, the curves of the corresponding nation are displayed as a gray line. Values were normalized using the presented spatial units. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
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S5 Fig. Absolute and relative change of urban sprawl values between 1990 and 2014 at the scale of a 50 × 50 km^2 grid. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Behrmann. All map contents comply with

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S6 Fig. Absolute and relative change of urban sprawl per capita values between 1990 and 2014 at the scale of a 50 × 50 km² grid. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Behrmann. All map contents comply with PLOS license CC-BY 4.0.
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S7 Fig. Differences in built-up area between GHSL and GUF at the scale of a 50 × 50 km² grid. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Map made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Behrmann. All map contents comply with PLOS license CC-BY 4.0.
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S8 Fig. Absolute differences (upper map; ΔWUP_p) and qualitative relations (lower map; sprawl classes) between GHSL and GUF based urban sprawl values at the scale of national units. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Hammer Wagner. All map contents comply with PLOS license CC-BY 4.0.
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S9 Fig. Absolute differences (upper map; ΔWUP_p) and qualitative relations (lower map; sprawl classes) between GHSL and GUF based urban sprawl values at the scale of subnational units. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Hammer Wagner. All map contents comply with PLOS license CC-BY 4.0.
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S10 Fig. Absolute and qualitative differences between GHSL and GUF based urban sprawl values at the scale of 50 × 50 km² grid cells. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Behrmann. All map contents comply with PLOS license CC-BY 4.0.
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S11 Fig. Data comparison GHSL-GUF: Jinjinji (China). Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_

globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S12 Fig. Data comparison GHSL-GUF: Burkina Faso. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S13 Fig. Data comparison GHSL-GUF: Netherlands and Belgium. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S14 Fig. Data comparison GHSL-GUF: United Kingdom. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S15 Fig. Data comparison GHSL-GUF: New York (US). Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. Maps made with Natural Earth and GADM: Natural Earth 4.0 @ naturalearthdata.com, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S16 Fig. Changes in WUP_p [UPU/m^2] values due to the exclusion of irreclaimable areas (barren or minimal vegetation, ice/snow) from the reporting units (countries and subnational units with $\Delta WUP_p > 0.1$ UPU/m^2) in 2014. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. World Land Cover 30m BaseVue 2013 @ MDAUS (https://landscape6.arcgis.com/arcgis/rest/services/World_Land_Cover_30m_BaseVue_2013/ImageServer).
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S17 Fig. Patterns of urban sprawl in agglomerations at the scale of a 1 × 1 km^2 grid: Moscow. Characteristics for the two urban sprawl metrics WUP_p and $WSPC$ and their dimensions LUP_p, DIS and PBA. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Maps made with GADM: Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Orientation map: OpenStreetMap contributors. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S18 Fig. Patterns of urban sprawl in agglomerations at the scale of a 1 × 1 km^2 grid: Montréal. Characteristics for the two urban sprawl metrics WUP_p and $WSPC$ and their dimensions LUP_p, DIS and PBA. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Maps made with GADM: Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Orientation map: OpenStreetMap contributors. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S19 Fig. Patterns of urban sprawl in Europe at the scale of a 1 × 1 km^2 grid: "Blue Banana" region. Characteristics for the two urban sprawl metrics WUP_p and $WSPC$ and their dimensions LUP_p, DIS and PBA. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Maps made with GADM: Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Orientation map: OpenStreetMap contributors. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S20 Fig. Coastal areas affected by high urban sprawl at the scale of a 1 × 1 km^2 grid: Los Angeles. Characteristics for the two urban sprawl metrics WUP_p and $WSPC$ and their dimensions LUP_p, DIS and PBA. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Maps made with GADM: Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Orientation map: OpenStreetMap contributors. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S21 Fig. Coastal areas affected by high urban sprawl at the scale of a 1 × 1 km^2 grid: French Riviera. Characteristics for the two urban sprawl metrics WUP_p and $WSPC$ and their dimensions LUP_p, DIS and PBA. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Maps made with GADM: Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org. Orientation map: OpenStreetMap contributors. Map Projection: Mollweide. All map contents comply with PLOS license CC-BY 4.0.
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S1 Table. Input datasets to measure urban sprawl at the global scale. The table provides all relevant information about the data products used for the study.
(PDF)

S2 Table. Urban sprawl values from global to national (top 40) scale. WUP_p 1990, 2000, 2014 (sorted descending by 2014 values), change in urban sprawl 1990–2014 (ΔWUP_p, ranking for absolute change), weighted sprawl per capita ($WSPC$, ranking for 2014). Data Sources:

European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
(PDF)

S3 Table. Values of urban sprawl components Dispersion, Percentage of built-up area, and Land uptake per inhabitant from global to national (top 40 WUP_p) scale. 1990, 2000, 2014 (sorted descending by WUP_p for 2014). Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
(PDF)

S4 Table. Highest 50 urban sprawl values at the subnational scale. WUP_p 1990, 2000, 2014 (sorted descending by 2014 values), change in urban sprawl 1990–2014 (ΔWUP_p), weighted sprawl per capita (*WSPC*). Excluding subnational units <100 km^2. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
(PDF)

S5 Table. Values of urban sprawl components Dispersion, Percentage of built-up area, and Land uptake per inhabitant at the subnational scale 1990, 2000, 2014. Top 50, administrative area > 100 km^2, sorted descending by WUP_p 2014. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0, Global Administrative Boundaries (GADM 3.6, 2018) @ gadm.org, Natural Earth 4.0 @ naturalearthdata.com.
(PDF)

S6 Table. Chi-Square Independence Test (classes: WUP_p & *HDI*, subnational, 2014). Data Sources: Global Data Lab (GDL) @ Radboud University: https://globaldatalab.org/shdi/; European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Chi-Square Test of Independence in R (sthda.com 2016).
(PDF)

S7 Table. Chi-Square Test: residuals (classes: WUP_p & *HDI*, subnational, 2014). Data Sources: Global Data Lab (GDL) @ Radboud University: https://globaldatalab.org/shdi/; European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Chi-Square Test of Independence in R (sthda.com 2016).
(PDF)

S8 Table. Chi-square test: Contribution of each cell to the total Chi-square score as percentage (classes: WUP_p & *HDI*, subnational, 2014). Data Sources: Global Data Lab (GDL) @ Radboud University: https://globaldatalab.org/shdi/; European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Chi-Square Test of Independence in R (sthda.com 2016).
(PDF)

S9 Table. Descriptive statistical summary of WUP_p values based on different input data-sets. Data Sources: European Commission, Joint Research Centre (JRC): ghs_pop_gpw4[1975|1990|2000|2015]_globe_r2015a_54009_250_v1_0, ghs_built_lds[1975|1990|2000|2014]_globe_r2016a_3857_38_v1_0. Global Urban Footprint (GUF) @ DLR 2016. World Land Cover 30m BaseVue 2013 @ MDAUS (https://landscape6.arcgis.com/arcgis/rest/services/World_Land_Cover_30m_BaseVue_2013/ImageServer).
(PDF)

S10 Table. List of countries and autonomously governed parts of a patron nations that were included in the analysis at the national scale. Data source: ISO 3166 country codes, UN member states @ un.org.
(PDF)

S1 Data. Data sheet with urban sprawl values (1990, 2000, 2014) for different spatial scales and a data description sheet.
(XLSX)

S1 Text.
(PDF)

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