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Urban Land Expansion and Decreased Urban Sprawl at Global, National, and City Scales during 2000 to 2020

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Land area in urban use may be growing faster than population growth, increasing urban sprawl. With calibrated population density thresholds from the Worldpop population model, area and densities can be measured for suburban and urban density classes (≥ 250 humans per square kilometer) at global and national scales and both broad multi-city agglomerations and fine city cores during 2000 to 2020. Globally, net expansion of suburban and urban, urban, and high-density urban area was 930,000, 545,000, and 215,000 km^2, respectively, with 25% to 35% of expansion located in India. Area containing suburban and urban densities increased from 3.4% to 4.1% of total land area. Density increased from 960 to 1,124.5 humans per square kilometer; density of the suburban class (250 to 800 humans per square kilometer) remained stable, while urban densities increased. Increased or stable densities occurred for nearly all countries and cities at both broad and fine scales, with the exception of 12 of 154 countries, 368 of 4,672 city agglomerations, and 523 of 12,008 city cores. Even though urban expansion occurred, as opposed to sustainable land use with growth boundaries, overall human densities increased. Human populations have become more concentrated, meaning that urban population densities are growing faster than the urban land base.

Introduction

Urbanization is a major trend in population demographics during the past century, typically exhibiting a pattern of rapid rural to urban shifts followed by sustained urban increases. However, countries exhibit a range of trajectories, including rare urban declines concurrent with rural growth as well as urban and rural growth, and in some cases, rapid urbanization rates may be due to modest urban population growth in combination with rural population declines [1]. Greatest urban growth is projected to occur in less urbanized countries, particularly those in Africa [1]. Urban areas, with concentrated businesses, health care, and education, offer greater earning potential and other opportunities than rural areas. Urban living may be associated with greater levels of literacy and education, socioeconomic status of women, access to social services, legal rights, and cultural and political participation [2].

Land conversion to the built environment occurs with growth in populations. Globally, urban land is estimated to be expanding at double the rate of population growth [3], with tripling occurring in some regions [2]. However, recent research suggests the opposite trend of population densification [4,5]. In accordance with the narrative of increasing sprawl, projections indicate that total amount of urban land could increase by 2- to 6-fold, with per capita urban land doubling or tripling (range of 1.1 to 4.9) across different socioeconomic scenarios over the 21st century [6]. Not only are cities expanding beyond administrative boundaries into agglomerations, but mega-urban regions emerge from the merger of multiple urban agglomerations, generating huge continuous urban areas that create challenges for land and transport governance [7].

Urban expansion may occur through either compact urban design or sprawl, with associated multifarious economic, social, and ecological consequences. Sprawl is land-consuming dispersed expansion, typically unplanned, with ecological and socioeconomic consequences due to increased environmental footprint and loss of access to urban amenities [8,9]. Car-oriented or human-oriented urban designs and lifestyles generate different, reinforcing outcomes. One element of urban sprawl is car dependency, which arises from multiple drivers due to prioritization of ever-increasing road density to accommodate rising traffic volumes for access to basic services and employment rather than prioritization of services and employment within walking distances of housing. Conversely, compact urban development through densification, reutilization of abandoned lots (i.e., greyfields), and reclamation of brownfields, intermixed with green spaces, promotes sustainability, livability, equity, health, and well-being, along with reduction of resource use [10]. Green spaces provide critical ecosystem services to cities, including flooding reduction, improved water quality, and contribution to well-being [11]. Regardless of planning or other influences, overall city growth and human behavior may take similar forms, with smart growth or compact city planning producing weak responses or unintended consequences, such as low-density housing with noncontiguous or leapfrog characteristics beyond zoning boundaries [12,13].

Nevertheless, cities display a wide range of population densities, representing many possible outcomes.

From an ecological perspective, compared to concentrated development, dispersed development appropriates more land and natural resources, resulting in greater ecosystem loss and degradation, along with loss of ecosystem services [9]. Urban land use is the most extreme wildland conversion due to near complete loss of vegetation cover along with sealing of soil surfaces by concrete and other building materials, which makes this land use relatively irreversible. Built environments modify biogeochemistry, hydrology, surface energy balance, and geomorphology, along with loss of soil function after sealing of soil surfaces [2]. Additionally, urbanization may result in increased exposure to pollution in many forms, including chemical, light, and noise, along with non-native species introduction. However, electricity, water, sanitation, roads, and other services for densely settled urban populations often are more efficient and thus less expensive and environmentally damaging, compared to provisioning the same number of people dispersed over rural areas. Lower-density human populations may consume more resources and produce more waste compared to higher-density populations; energy consumption and greenhouse gas emissions may be double to quintuple in low-density suburban or rural development compared to high-density urban cores [9,14].

The spatial configuration of sprawl also is an ecological consideration because continuous urban agglomerations will reduce intermixing and fragmentation of ecosystems compared to scattered developments with porous infilling. However, mega-urban regions, such as those that occur along low-elevation coastal zones (e.g., the United States Atlantic Coast stretching from south of Philadelphia, Pennsylvania to north of New Haven, Connecticut), offer a solid interface with little natural permeability, posing additional challenges. Coasts and floodplains are flyways for migratory birds, and mega-urban regions offer limited resources and shelter to birds during migration, when massive die-offs can occur while inclement weather mixes with starvation and dehydration. Additionally, contiguous development is a barrier to species movement, whereas buildings, communication towers, and wind turbines directly cause mortality to flying animals. Continuous development may displace most rare and endemic species with limited ranges that are not present outside of the agglomeration envelope. Urbanization often occurs on flat, fertile agricultural lands, which were once productive wildlands [9]. Nevertheless, some plants and pollinators may function in smaller spatial scales, such as the scale of green spaces, than many other species [15].

No consensus exists in either the definition, measurement, or impact of urban or urban sprawl [3,10,16–18]. The lack of consensus is because urbanization encompasses multifaceted social, economic, political, and demographic histories, but to allow international comparability of variable national definitions, a measurable definition of what constitutes urban is necessary based on quantification of greater density in either populations or the built environment [4,19,20]. Six international organizations and agencies developed the degree of urbanization approach, based on population size of settlements, to delineate cities and urban and rural areas [4]. An alternative method is application of population density classes, already calibrated from urban percentage to the United Nations 2015 global urban population estimate of 53.9% derived from census data ([21]; this urban percentage is decided by cumulative national reporting and has acceptance) and then balanced among three 2015 population models to reach approximately the same population percentages for rural, suburban, urban low, and urban high density by density thresholds, which varied by population model [19]. The Worldpop and Landscan population models [22,23] had the least country-wise divergence from U.N. national urban percentages. Moreover, Worldpop and Landscan conform with other population models, while being intermediate in spatial population distribution, that is, not the extreme model for population dispersion or concentration, unlike other population models. Other research has demonstrated that Worldpop and Landscan population models tend to perform most accurately [24–26]. However, only Worldpop provides density models that are similarly modeled for each year and compatible over a time interval of decades. These approaches, and building-based definitions, have highlighted inconsistencies in national urban reporting and, moreover, questioned assumptions about urban narratives [20].

Regarding sprawl, general agreement is that sprawl is an expression of suburbanization or lower-density development of the built environment surrounding cities that outpaces population growth rates [8,9,27,28]. Consequently, it may be critical to separate the multidimensional definitions of sprawl clearly into wildland and ecosystem loss, from an ecological perspective, compared to socioeconomic components such as livability and accessibility or car dependency, from a human perspective. Density is an essential measure for sprawl [28], directly addressing the ecological aspects of how concentrated humans are on a land base while density also is a component of the social dimension. Here, I focused on changes in area and density during 2000 to 2020 at global, national, and 2 city scales to quantify expansion in urban and suburban lands and identify locations and magnitude of increased sprawl compared to population densification. The definition of urban land was urban population densities ≥ 800 humans per square kilometer, with urban high population densities ≥ 1,900 humans per square kilometer, and suburban densities ≥ 250 humans per square kilometer' using the Worldpop population model ([19,29,30]; Table). To emphasize critical details for measuring city sprawl [10], as opposed to administrative boundaries, both urban core areas and broad urban agglomerations, with additional buffers, were the analysis windows. The 2 windows were constant but only measured mean density for areas that were ≥ 250 inhabitants per square kilometer, which varied over time, to collect densities for both suburban and urban populations. Where density decreased over time, area changes will indicate whether density decreases were due to greater expansion rates in land area compared to population growth or alternatively, depopulation, where area decreased to below suburban density levels but generally the infrastructure remains as opposed to land restoration. To address the human dimension of sprawl, I also supplied densities for urban high-population-density areas (≥1,900 inhabitants per square kilometer), as a simple measure that may be an advancement compared to no common methodology applied globally. Formally, my question was: Has sprawl increased at global and national scales and both broad multi-city agglomerations and fine city cores during 2000 to 2020?

Materials and Methods

Population density dataset

For global population densities, all Worldpop models are available for comparison from 2000 to 2020 (i.e., models from each

Table. Population densities (inhabitants per square kilometer) and area (square kilometer) for 4 different classes and mean population density for suburban, urban low, and urban high density classes during 2000, 2010, 2015, and 2020 for the Worldpop population model. Different population models will require tailored threshold adjustments.

		2000		2010		2015		2020	
Threshold	Class	Density		Density		Density		Density	
0 to 250	Rural	11		11		11		11	
250 to 800	Suburban	438	960	437	1,010	437	1,072	437	1,124
800 to 1,900	Urban low	1,165		1,173		1,179		1,185	
>1,900	Urban high	4,791		4,861		4,958		5,100	
Threshold	Class	Area		Area		Area		Area	
0 to 250	Rural	128,993,794		128,476,258		128,326,427		128,058,349	
250 to 800	Suburban	3,342,376		3,608,737		3,619,921		3,726,059	
800 to 1,900	Urban low	852,630		1,015,198		1,085,989		1,184,293	
>1,900	Urban high	392,070		476,593		543,082		606,685	

year are compatible, despite any model improvement). Worldpop populates census data throughout census blocks with model variables including land cover, urban land use, transportation networks and travel times, distance to roads, slopes, and nighttime lights (cell size of 0.0083 degrees, 30 arc-seconds; [29–31]). Population counts are meant to remain unprojected in the World Geodetic System 1984 geographic (longitude/latitude) coordinate system to maintain data fidelity [22]. Cell areas in square kilometers [32] permitted measurement of area and calculation of population density.

Suburban and urban city agglomerations and urban city cores

For cities, given that administrative boundaries are not equivalent to the metropolitan and micropolitan populations, suburban and urban city agglomerations and urban city cores provided 2 analysis windows. For urban agglomerations, extracted from Landscan population density data (Natural Earth [33]), an added 0.1 decimal degree buffer around each agglomeration captured recent growth and missing suburban densities. Combination of overlapping agglomerations generated 4,672 cities or multi-cities, renamed by up to the first 5 cities in alphabetical order. For a more precise focus on urban densities, the Global Human Settlement Layer Global Urban Centres [34] supplied 12,259 named cities. These 2 extents helped balance the possibility of too much merged urban area compared to not encompassing the entire urban area.

Calculation of urban sprawl and land expansion

For global urban sprawl and land expansion, I calculated density and area in the urban high (≥1,900 inhabitants per square kilometer), urban low (≥800 inhabitants per square kilometer), and suburban density (≥250 inhabitants per square kilometer) classes during 2000, 2010, 2015, and 2020. To determine sprawl at country and city scales, I calculated density and area in (a) the urban high, urban low, and suburban density classes (≥250 inhabitants per square kilometer) for countries with ≥1 million inhabitants (covering 99.4% of global suburban and urban land area; Natural Earth [35]), (b) coarse city agglomerations that encompassed a large suburban extent, and (c) finer city urban cores during years 2000 and 2020. I distinguished locations where densities in the suburban and urban area of the density classes changed in density over time and then assessed whether this area decreased, indicating depopulation rather than expansion. To exclude locations that were relatively stable or had error arising from modeling or population measurement, I identified countries (all of which had area of the urban high, urban low, and suburban density classes ≥ 150 km^2) and cities with area of the urban high, urban low, and suburban density classes ≥ 150 km^2 that changed in density during 2000 to 2020 in excess of 5% of the 2000 country density. For example, if a location had a mean density of 1,000 inhabitants per square kilometer during 2000, density increases or decreases during 2000 to 2020 needed to exceed 50 inhabitants per square kilometer at the 5% threshold. Likewise, I isolated cities with area of the urban high, urban low, and suburban density classes between 50 and 150 km^2 that changed in density in excess of 10% of the 2000 city density and cities with area of the urban high, urban low, and suburban density classes < 50 km^2 that changed in density in excess of 15% of the 2000 city density.

Results

Global

Globally, although the area of suburban and urban densities (≥ 250 humans per square kilometer with the Worldpop model) increased over the time interval, density increased from 960 humans per square kilometer during 2000 to 1,124.5 humans per square kilometer during 2020 (Table). These density values were consistent overall with the urban low-density class. Density of the suburban class (250 to 800 humans per square kilometer) remained stable, while urban densities increased. During 2000, area of the suburban and urban densities was 3.4% of total land area, of which 2.5% was suburban area. During 2020, area of suburban and urban densities was 4.1% of total land area, of which 2.8% was suburban area. Percentage of the population in the area of the suburban and urban densities remained steady at 77.2%, even though population increased. The net difference in area of suburban and urban densities was approximately 930,000 km^2 during 2000 and 2020, whereas the net difference in area of urban and urban high population density classes was 545,000 and 215,000 km^2, respectively. Conversion by decade decreased for area of suburban and urban densities, with 55% of net areal expansion occurring during 2000 and 2010 and 45% during 2010 to 2020, whereas conversion by decade increased for urban and urban high population density classes, with 55% and 60% of net areal expansion occurring during 2010 to 2020, respectively.

National

Overall, at the country scale (populations ≥ 1 million), the area of suburban and urban densities expanded by 994,913 km^2, whereas depopulation occurred on 77,068 km^2 (Table S1). India contained 26% of the suburban and urban expansion, whereas another 36% of the expansion occurred in Nigeria, Pakistan, Democratic Republic of the Congo, Ethiopia, Uganda, United States, Indonesia, and Kenya, descending in value from 8% to 2% of areal expansion. China contained 37% of the area of suburban and urban depopulation, followed by Burma/Myanmar (21% of depopulation, with some error resulting from the ghost city of Naypyidaw), Germany (11%), Japan (10%), Ukraine (5%), Turkey (4%), and Russia (4%). Urban area expanded by 556,741 km^2, with most expansion in India (35%) and China (13%), along with 13,461 km^2 of depopulation, primarily in Burma/Myanmar (48% of depopulation, with some error) and Japan (27%). For high-density urban area, expansion increased by 216,872 km^2, with most expansion in India (24%) and China (13%), followed by the United States, Nigeria, Indonesia, Pakistan, Bangladesh, Egypt, and Brazil, descending in value from 6% to 2% of areal expansion, along with 3,239 km^2 of depopulation, primarily in Burma/Myanmar (43% of depopulation, perhaps an error), Russia (29%), and Ukraine (15%).

For the area of suburban and urban densities, 154 countries (populations ≥ 1 million) overall increased in density (area-weighted) from 951 humans per square kilometer to 1,118 humans per square kilometer (Table S1). Following the 5% threshold of change in density compared to 2000 density to allow for relative stability and error, 35 countries, comprising 360 million inhabitants, remained relatively stable in density, increasing in density from 1,167 to 1,190 humans per square kilometer with areal expansion in 25 countries of 32,061 km^2 and depopulation in 10 countries of 7,728 km^2. For 12 countries, containing 170 million inhabitants, density decreased from 1,044 to 920 humans per square kilometer, with 92,076 km^2 of increased area in 9 countries and depopulation in 3 countries on 15,991 km^2 (Fig. 1). Chad, Kuwait, Somalia, Niger, Papua New Guinea, France, Senegal, Democratic Republic of the Congo, and Mozambique increased in area. Burma/Myanmar, Moldova, and Republic of the Congo decreased in the area of urban high and urban low classes, indicating either depopulation or error. The decrease in Burma/Myanmar density may be error arising from the presence of Naypyidaw, a large city constructed independent of residents, which was assigned a dense population for 2000 but not 2020. Most countries (107, containing 5.6 billion people) increased in density, from 934 to 1,120 humans per square kilometer, along with expansion in 95 countries on 870,777 km^2 and depopulation in 12 countries on 53,349 km^2 (Fig. 1).

Agglomerations

The 4,672 city or multi-city agglomerations comprised almost 4.6 billion individuals during 2020, or 60% of the global total. Overall, density increased from 1,142 humans per square kilometer to 1,447 humans per square kilometer, with expansion by 69% of cities in 339,654 km^2 and depopulation in the remaining 1,140 cities of 101,757 km^2. The 1,335 stable cities, of 306 million people, had densities that maintained about 1,445 humans per square kilometer, with expansion by 58% of cities on 19,313 km^2 and depopulation over 9,126 km^2. The 368 decreasing cities, enclosing 113 million people, decreased from 1,546 to 1,233 humans per square kilometer, with expansion by 60% of cities across 19,707 km^2 and depopulation covering 3,925 km^2 (Figs. 2 and 3). The city with the greatest decrease was Naypyidaw, Burma/Myanmar, which is an uninhabited "ghost" city, and a correction must have been applied to later census data or recent versions of Worldpop. The 2,969 increasing cities, with 4.16 billion people, increased from 1,108 humans per square kilometer to 1,454 humans per square kilometer, with expansion by 75% of cities on 300,634 km^2 and depopulation across 88,707 km^2 (Figs. 2 and 3).

Cores

Of the 12,259 city cores, 12,008 contained suburban and urban areas, containing 2.74 billion individuals during 2020. Density (area-weighted) overall increased from 3,247 to 4,461 humans per square kilometer, along with expansion of suburban and urban densities of 10,179 km^2 and depopulation by 5% of cities on 698 km^2. Additionally, 81% of cities were small as defined by <50 km^2 in area of the urban high, urban low, and suburban density classes. Of the 12,008 cities, 1,549 cities generally were stable in density, following the density change thresholds by area, and contained 309 million inhabitants. Nevertheless, density increased from 3,248 to 3,280 humans per square kilometer, along with expansion of suburban and urban densities on 404 km^2, whereas 15% of cities experienced depopulation over 257 km^2. About 70% of cities were small based on suburban and urban areas. A total of 523 cities, containing 93 million inhabitants, decreased from 3,608 to 3,061 humans per square kilometer, with 269 km^2 of increased area and 208 km^2 of decreased area (Figs. 2 and 3). About 20% of cities decreased in area, indicating depopulation; 77% of cities were small in terms of suburban and urban areas (Figs. 2 and 3). For 9,936 increasing cities, which contained the bulk of the population (2.34 billion), density increased from 3,224 to 4,776 humans per square kilometer, along with expansion of suburban and urban densities on 9,505 km^2 and 2% of cities had depopulation on 233 km^2; 83% of cities were small in area (Figs. 2 and 3).

Discussion

Urban expansion with population concentration, not sprawl

One concern is that sprawl has been increasing, but this approach demonstrated that while expansion of suburban and urban classes (≥250 humans per square kilometer with the Worldpop model) has occurred, urban population densities have increased while suburban population densities have remained stable. Urban and suburban development expanded a net area of 930,000 km^2 during 2000 to 2020 with concentrated population density, specifically in the urban population classes (≥800

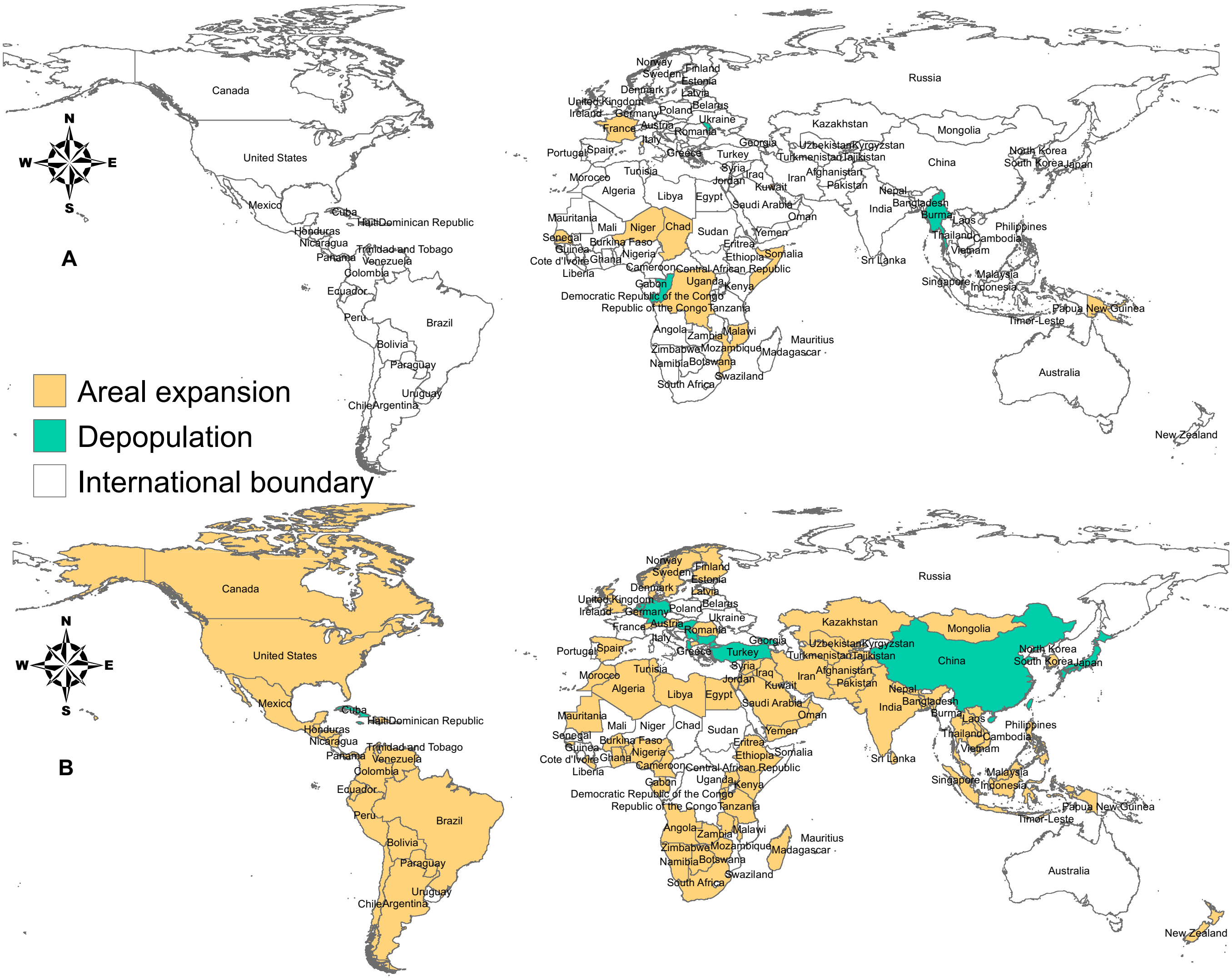

Fig. 1. Countries that (A) decreased or (B) increased in urban and suburban density (≥250 inhabitants per square kilometer) between 2000 to 2020, accompanied by either areal expansion or depopulation. (The figure is in the World Geodetic System [WGS] 1984 geographic coordinate system.)

humans per square kilometer), rather than dispersed populations. A total of 995,000 km^2 of urban and suburban expansion occurred in 154 countries, primarily India, with depopulation in 77,000 km^2, primarily China. Although urban land expansion is not a sustainable pathway, net area of urban and suburban expansion decreased by almost 100,000 km^2 between decades. For perspective, 1,000,00 km^2 is an area greater than Egypt and 125 other countries (with populations ≥ 1 million) and 100,000 km^2 is an area greater than Portugal and 52 other countries. Similar expansion with concentrated density occurred for cities at both broad and fine windows. Nonetheless, 12 of 154 countries, 368 of 4,672 broad city agglomerations, and 523 of 12,008 fine city cores decreased in density in the area of suburban and urban classes. These findings of overall population concentration, rather than sprawl, concur with Schneider et al. [5] and Dijkstra et al. [4].

Countries and major cities that decreased in density appeared to be representing different population trends of sprawl and depopulation. Countries with density decreases generally were located in Africa, a continent that is growing in population [1]. France was one exception, but according to the 2011 census, France's population grew at a faster rate than most other countries across the globe [36]. Conversely, cities that decreased in density generally were located in eastern Europe, Russia, and China, which also were countries where overall densities increased along with depopulation, or abandonment of some area with suburban and urban densities during 2000. This may be detection of urban decay. Albania, Bulgaria, China, Cuba, Georgia, Germany, Hungary, Jamaica, Japan, Netherlands, Serbia, and Turkey were countries that increased in density in part due to losses of suburban and urban areas (Fig. 1).

These findings of concentrating populations over time contrasted with the existing perspective that urban land generally is expanding twice as fast as populations growth and mean population density of built-up areas in all cities, regions, and population sizes is decreasing [3,14,37]. This research has remained influential, with few studies to the contrary. Nevertheless, Schneider et al. [5], by applying satellite imagery and census data for >1,000 agglomerations in the East–Southeast Asian region, found that whereas urban land increased >22% between

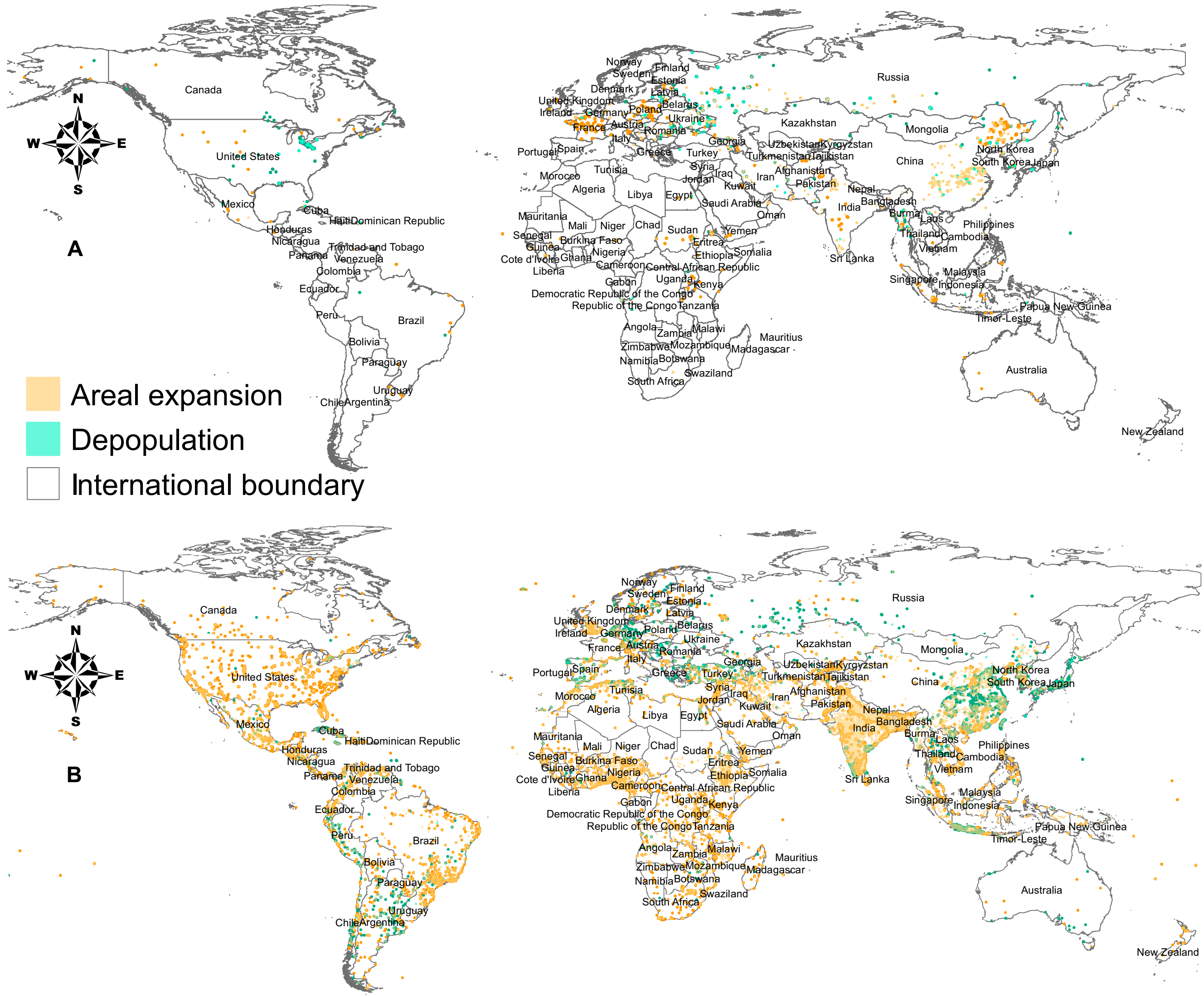

Fig. 2. Cities that (A) decreased or (B) increased in urban and suburban density (≥250 inhabitants per square kilometer) between 2000 to 2020, accompanied by either areal expansion or depopulation. Lighter color shades indicate changes occurred in the fine city cores. (The figure is in the WGS 1984 geographic coordinate system.)

2000 and 2010 (from 155,000 to 189,000 km^2), urban populations grew more rapidly, producing increased densities. Dijkstra et al. [4] determined that cities have become denser over time, except small ones.

Discrepancies with earlier findings may result from several sources. Urban land is variously defined [3,17], but for global results, I provided 3 different levels, ranging from all urban land encompassing suburban densities, which is the area of new urban expansion and potential sprawl, to global impervious surface area in cities with high urban densities. For Seto et al. [3], global urban land cover projections corresponded with urban and suburban land, based on increases covering about 1,527,000 km^2 by 2030. This projection almost exactly corresponds with the urban and suburban land gain in this study of about 500,000 km^2 per decade during 2000 to 2020, or specifically, a net gain of 515,000 km^2 during 2000 to 2010 and a net gain of 415,000 km^2 during 2010 to 2020. Seto et al. [3] documented increased sprawl during 1970 to 2000. Before 2000, different expansion patterns occurred [27], but given comprehensive densification at global, national, and city scales during 2000 to 2020, and during 2000 to 2010, the pattern seems unlikely to globally have reversed from sprawl during 1970 to 2000 without strong, identified drivers of change. Therefore, it may be that, in part, Seto et al. [3] detected increased sprawl because studies for 292 geographic locations in 67 countries were biased, in that known cases of sprawl were selected. Without selection in this study, for 156 countries with populations ≥ 1 million and covering 99.5% of suburban and urban land area, a total 870,000 km^2 of suburban and urban expansion was concurrent with increased population densities, whereas 92,000 km^2 exhibited reduced densities. The cities with either broad suburban extents or fine urban extents encompassed respectively 300,000 or 10,000 km^2 of suburban and urban expansion with increased densities and 20,000 or 300 km^2 of expansion with reduced densities. Another option that may explain disagreement is measurements or poor population data because census data can be inaccurate along with pitfalls such as reporting by administrative boundaries [8,10].

The implication of urban expansion but with population concentration instead of sprawl is that this is an alternative

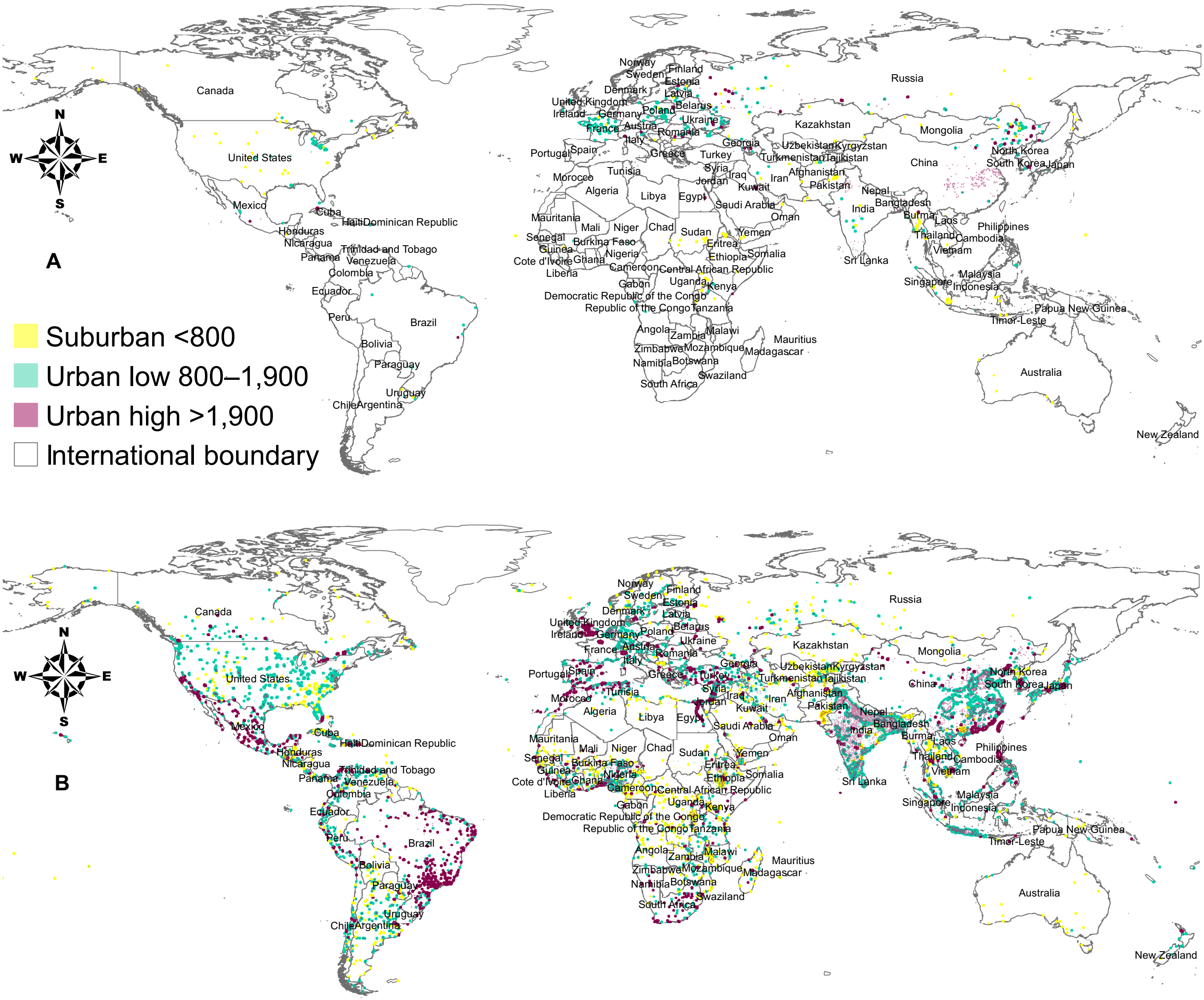

Fig. 3. Densities for cities that (A) decreased or (B) increased in urban and suburban density (≥250 inhabitants per square kilometer) between 2000 to 2020. Lighter color shades indicate changes occurred in the fine city cores. (The figure is in the WGS 1984 geographic coordinate system.)

narrative to old assumptions, opening new research avenues. Rather than the widely held notion of sprawl, which is communicated in publications, urban land use is the issue. The key focus can be continuing to curtail urban land expansion and concentrate population densities. The limited locations of sprawl can be examined for driving factors, while rural sprawl may be considered.

Sprawl as a measure of livability

Densities for areas of urban high densities (≥1,900 inhabitants per square kilometer) may be useful for where sprawl never has been measured or to place sprawl measurements on an equal basis across countries. Density in the urban high class likely captures sprawl from the human perspective. For example, out of 324 cities in the United States, New York was most dense (6,585 inhabitants per square kilometer in the finer city extent) while Los Angeles ranked 15th. Los Angeles is challenging to separate in rankings because Los Angeles is one of the most compact cities, despite being sprawling in terms of human dimensions, that is, car-oriented with traffic congestion and lacking a city core. More complicated measures have not created substantially greater separation for Los Angeles, ranked 21 of 221 cities [38]. Socioeconomic measures that incorporate car dependency, access to services, and employment options have been developed to address human concerns, but these measures remain influenced by the benefits of large cities rather than clearly separating out the transportation component. Deilmann et al. [39] found that larger cities generally have less unemployment and other economic indicators and more services than smaller cities.

Although generally larger cities have greater population densities than smaller cities, smaller cities did not appear to sprawl with the growth process, as a greater percentage of small cities compared to large cities increased in density as opposed to decreasing in density. It may appear that core population density is not enough to offset growth until development of attached houses, apartments, and high-rise buildings, but land parcels will become progressively smaller in the valuable city center. Lots will remain large on the outskirts, but these may be areas of exurban densities. Exurban area thus may be exhibiting the pattern of land increases at faster than population growth rates; however, rural sprawl is a separate issue from urban sprawl.

It is possible that most cities are not planned efficiently, with services within walking distance or else convenient mass transit, and city centers are a very small percentage of city areas. If cities are dense, a functional city center is not critical to detect in sprawl measurements. Lopez and Hynes [10] remarked that, with perhaps the exception of walled or physically bounded cities, all urban areas display some sprawl characteristics, such as homes separated from employment and amenities, road networks, and lack of activity centers. Urban intensification that increases population density may reduce per capita car use but may increase local concentrations of motor traffic, unless accompanied by vehicle restrictions [40]. Denser cities with more traffic congestion may have the benefit of shorter commutes [41]. Cities may be filled with commuters and an extremely high road density that covers livable space or have mass transit, and these 2 alternatives will either have adverse consequences or benefits.

Limitations

The Worldpop population model appears robust [24–26], along with density thresholds for suburban and urban densities, albeit refinement and calibration always are possible. Areas of suburban and urban densities fit reasonably well with measurements of urban land or a building-based definition of urban [17]. During 2000, global land area of urban high densities was 0.29%, which increased to 0.41% of total land area during 2015. Every model has different thresholds for categories, but these urban percentages were relatively similar to 0.48% of land area in the dense and semidense urban land cover of the Global Human Settlement grid [42] during 2014 and 0.58% of land area (excluding permanent snow and ice) for European Space Agency Land Cover [43] during 2015, and additional sources of measurements in the 0.28% to 0.65% range [17]. The area of suburban and urban densities was 3.4% of total land area during 2000, which matches with measurements of 3% urban land [17].

Other limitations involve measurement error. Sources of uncertainty arise from population census data and the estimation of the urban populations [1,36]. Indeed, the Worldpop population model may provide the best foundation for any applications of population information, such as past growth and future projections. Worldpop distributes populations from census data within census units, overall strengthening population data while carrying some weaknesses [5]. For example, error was apparent in Naypyidaw, Burma/Myanmar, an uninhabited "ghost" city, which was overpopulated in the model during 2000 but not during 2020.

Urban definitions and sprawl encompass more than simple metrics of land use at different population densities, incorporating services, economic opportunities, employment options, and infrastructure associated with urban life [38]. Nonetheless, Worldpop and other population models permit consistent urban definitions. While thresholds place continuous values into discrete classes, density classes are interpretable and set reasonable anchor points for measuring urban and suburban growth.

Conclusions

This study is an application of a global assessment of suburban and urban expansion and changing sprawl over time across all major countries and cities, grounded on human population density in the area of suburban and urban classes (densities ≥ 250 humans per square kilometer with the Worldpop model) during 2000 and 2020. Globally, net expansion of suburban and urban, urban, and high-density urban area was 930,000, 545,000, and 215,000 km^2, respectively, with 25% to 35% of expansion present in India. Despite expansion, population densities increased during 2000 to 2020, indicating that population growth concentrated relative to land area. To better understand urbanization and inform new urban development, it may be important to separate the definition of sprawl into land consumption, or an ecological perspective, from car dependency and complex socioeconomic measures of sprawl. These results provided alternative evidence to the existing narrative that urban land is expanding at a faster rate than urban populations.

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Data Availability

Population data are available at http://www.worldpop.org.

Supplementary Materials

Table S1

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