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PERSPECTIVE

How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion

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Abstract Urbanization has transformed the world's landscapes, resulting in a series of ecological and environmental problems. To assess urbanization impacts and improve sustainability, one of the first questions that we must address is: how much of the world's land has been urbanized? Unfortunately, the estimates of the global urban land reported in the literature vary widely from less than 1–3 % primarily because different definitions of urban land were used. To evade confusion, here we propose a hierarchical framework for representing and communicating the spatial extent of the world's urbanized land at the global, regional, and more local levels. The hierarchical framework consists of three spatially nested definitions: "urban area" that is delineated by administrative boundaries, "built-up area" that is dominated by artificial surfaces, and "impervious surface area" that is devoid of life. These are really three different measures of urbanization. In 2010, the global urban land was close to 3 %, the global built-up area was about 0.65 %, and the global impervious surface area was merely 0.45 %, of the word's total land area (excluding Antarctica and Greenland). We argue that this hierarchy of urban land measures, in particular the ratios between them, can also facilitate better understanding the biophysical and socioeconomic processes and impacts of urbanization.

Keywords Urbanization · Global urban land · Urban area · Built-up area · Impervious surface · Hierarchy of definitions

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Introduction

The world has been urbanizing at an accelerating rate since the industrial revolution, resulting in a series of ecological and environmental problems (Irwin and Bockstael 2007; Grimm et al. 2008; Fragkias and Seto 2012; Wu 2013c, 2014). Urbanization has become a central topic in landscape ecology during the past few decades (Wu 2013b). To assess the effects of urbanization on biodiversity, ecosystem processes, and environmental conditions, we must know how much of the world's land has been urbanized in terms of its total amount and spatial distribution. With today's

remote sensing and GIS technologies, one would think that this question can be readily answered. This is far from the truth, however. The current estimates of the global urban land vary considerably, ranging from less than 1 % of global land area (Loveland et al. 2000; Schneider et al. 2003; Angel et al. 2005; Bartholome and Belward 2005; Elvidge et al. 2007; Goldwijk et al. 2010; Schneider et al. 2010; Angel et al. 2011; Demographia 2012) to 3 % of global land surface (Grimm et al. 2008; Gamba and Herold 2009; CIESIN et al. 2011). In addition to different data sources and methods, inconsistent definitions of "urban land" have been recognized as a primary reason for these discrepancies, which certainly needs clarification (McIntyre et al. 2000; McIntyre 2011; Raciti et al. 2012; Wu 2014).

Therefore, the objective of this study was to identify the best available estimates of the global urban land area based on a nested hierarchy of definitions. Specifically, we first reviewed the various definitions of urban land used in the literature, and then developed a hierarchical framework to clarify the relationship among the different definitions. Finally, we selected the best available estimates by comparing and contrasting the different studies based on the hierarchical framework.

Urban land—one variable, many definitions

The term "urban" has a number of different connotations in the literature, and comprehensive reviews on this topic already exist (McIntyre et al. 2000; McIntyre 2011). Three factors—total population size, population density, and impervious surface area or built structures—are commonly used as the criteria for defining what is urban (Wu 2014). For the purpose of this study, we did not think that it would be necessary to review all the definitions of urban land in the literature. Instead, we focused only on the urban land definitions that were used in the studies that estimated the global urban land area, as discussed below.

We reviewed 12 estimates of the global urban land area from publications between 1993 and 2013, which used six different definitions of "urban land" (Table 1). These estimates included nine based on various global urban land datasets (Angel et al. 2005; Bartholome and Belward 2005; Schneider et al. 2009; Elvidge et al. 2010; Goldwijk et al. 2010; Schneider et al. 2010; Angel et al. 2011; CIESIN et al. 2011; ESA 2011; Demographia 2012), one from the Worldwatch Institute's work on global cities (O'Meara 1999), and two from books on the world's urban land (Douglas 1994; Gamba and Herold 2009). The six definitions of urban land used in these 12 estimates are: "cities' area," "urban administrative area," "places dominated by the built environment," "built-up area," "artificial surfaces and associated areas," and "impervious surfaces."

The estimates of global urban land area vary widely among different definitions (Table 1). Under the definitions of "cities' area" and "urban administrative area," the estimated global urban land area was close to 2 % of the world's land area. When the other four definitions were used, however, the estimates were much lower—about 0.6 % or less. Furthermore, two studies, in which the global urban land was not explicitly defined, provided the highest estimates—over 2 % and close to 3 % (Gamba and Herold 2009; CIESIN et al. 2011). The results of this comparison indicate that the primary cause for the large discrepancies among the different estimates was the use of different definitions of what constituted the "urban land," admitting that differences in data sources and estimating methods may also have played a role. Clearly, streamlining the different definitions of the urban land is needed to avoid confusion.

A hierarchical framework for clarifying urban land definitions

To avoid or eliminate the confusion due to various definitions, here we propose a three-level hierarchical system of urban land definitions (Fig. 1), which is a nested definitional hierarchy in the parlance of hierarchy theory (Wu 2013a). This framework consists of three hierarchical levels, corresponding to three key definitions of urban land with decreasing spatial inclusiveness: "urban area" at the bottom, "built-up area" in the middle, and "impervious surface" at the top (Fig. 1).

The term "urban area" refers to the spatial extent of the most broadly defined urban land, closely corresponding to "urban administrative area" and the "cities' area" mentioned above. In other words, the urban area is the total area within the administrative boundaries of a city, including all the impervious surfaces, vegetated areas, barren land, and water

Table 1 Comparison of twelve estimates of the global urban land based on different definitions and data sources

Urban land definition	Estimate			Name of dataset (abbreviation)	Data source*** (spatial resolution)	Processing method	Website for downloading dataset (citation)
	Area (km^2)	% of total land area (%)	% of total land area* (%)				
Cities' area		2.00**		Worldwatch cities' area (WWCA)	UN urban population	Estimation based on population density	(O'Meara 1999)
Urban administrative area	2,470,000	1.68	1.86	Generalized approximation of urban land area (GAULA)	UN urban population	No description	(Douglas 1994)
Places dominated by the built environment	711,770 ~ 869,358	0.48 ~ 0.59	0.54 ~ 0.65	Global Urban Land Cover in 2010 (GULC2010)	MOD500 and UN urban population	Data fusion	http://www.lincolninst.edu/subcenters/atlas-urban-expansion/ (Angel et al. 2011)
	657,000	0.45	0.49	MODIS Urban Land Cover 500-m (MOD500)	MODIS multi-spectral imageries (500 m)	Supervised classification	http://www.sage.wisc.edu/ (Schneider et al. 2009, 2010)
Built-up area	615,752	0.42	0.46	History Database of the Global Environment V3.1-2010 (HYDE3.1-2010)	IGBP-DISCover map and GLC2000 (9 km)	Combination	http://131.224.244.83/en/themasites/hyde/index.html/ (Klein Goldwijk et al. 2010)
	423,703	0.29	0.32	Demographia World Urban Areas 2012 (DWUA2012)	Statistics and remote sensing data	Summarizing	http://www.demographia.com/#urban/ (Demographia 2012)
	409,000	0.28	0.31	World Bank Urban Area 2000 (WBUA2000)	Urban population and Landsat data	Data fusion	http://www.worldbank.org/urban/ (Angel et al. 2005)
Artificial surfaces and associated areas	318,334	0.22	0.24	Global Land Cover Product 2009 (GlobCover2009)	MERIS multi-spectral data (300 m)	Unsupervised classification	http://due.esrin.esa.int/globcover/ (ESA 2011)
	280,701	0.19	0.21	Global Land Cover 2000 (GLC2000)	SPOT/VGT NDVI data and DMSP/OLS nighttime light data (1 km)	Unsupervised classification	http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php/ (Bartholome and Belward 2005)
Impervious surfaces	595,971	0.40	0.45	Global Impervious Surface Area in 2010 (IMPSA2010)	DMSP/OLS nighttime light data and LSCAN (1 km)	Multiple linear regression	http://www.ngdc.noaa.gov/dmsp/ (Elvidge et al. 2010; Sutton et al. 2010)
Not explicitly defined		3.00**		Gamba and Herold' estimate of global urban area (GHGUA)	No description	No description	(Gamba and Herold 2009)

Table 1 continued

Urban land definition	Estimate			Name of dataset (abbreviation)	Data source*** (spatial resolution)	Processing method	Website for downloading dataset (citation)
	Area (km^2)	% of total land area (%)	% of total land area* (%)				
	3,506,830	2.38	2.64	Global Rural–Urban Mapping Project (GRUMP)	DMSP/OLS nighttime light data (1 km)	Thresholding (>0)	http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents/ (CIESIN et al. 2011)

* Total land area excludes Antarctica and Greenland

** Only the percentage of urban land was published

*** *DMSP/OLS* Defense Meteorological Satellite Programme's Operational Line Scanner, *IGBP-DISCover* International Geosphere–Biosphere Programme's Data and Information Systems global land Cover, *LSCAN* LandSCAN global population database, *MERIS* MEdium Resolution Imaging Spectroradiometer, *MODIS* MODerate resolution Imaging Spectroradiometer, *NDVI* Normalized Difference Vegetation Index, *SPOT/VGT* Systeme Pour l'Observation de la Terre's Vegetation Sensor, *UN* United Nations

bodies. The urban area of a larger geographic region that includes multiple cities is simply the total sum of urban areas of all the cities in the region. This administrative boundary-based urban definition has been used in the literature (Douglas 1994; McIntyre et al. 2000; McIntyre 2011).

We propose to use the term "built-up area" to replace similar definitions such as "place dominated by the built environment" and "artificial surfaces and associated areas." The built-up area of a geographic region is only part of its urban area –the portion that is dominated (more than 50 % in cover) by non-vegetated, human-constructed elements, such as roads, buildings, runways, and industrial facilities. Thus, the areas dominated by vegetation (e.g. golf courses and parks) within the administrative boundary of an urban area are not considered as part of the urban land (Potere and Schneider 2007).

At the top level of the definitional hierarchy is the "impervious surface," which refers to human-made land covers through which water cannot penetrate, including rooftops, roads, driveways, sidewalks, and parking lots (Ridd 1995; Weng 2012). For a given geographic region, the impervious surface area must be smaller than the built-up area which, in turn, must be smaller than the urban area (Fig. 1). For example, Sutton et al. (2010) found that, in Southeast Asia, the fraction of impervious surface was often much less than 50 % of the built-up area even in the core of large cities.

Quantifying urban land using the 3-level definitional hierarchy

How much of the world's land has been urbanized? The answer to this question clearly varies with the urban land definitions as discussed earlier. Using our proposed hierarchical framework, however, the answers become no longer confusing even though they still differ. For example, let us take a look at the most reliable estimates of the global urban land area (Table 2). The total amount of "urban area" of the world the global urban land was 1.86 % to 2.00 % of the world's land surface, excluding Antarctica and Greenland, according to Douglas (1994) and O'Meara (1999). Using more recent data sources, we estimated that the global urban area was about 3.00 % (Gamba and Herold 2009; CIESIN et al. 2011). The total amount of "built-up area" of the world was

Table 2 Estimates of the world's urban land based on the newly proposed nested hierarchy of urban definitions: impervious surface < built-up area < urban area

Urban land definition	Global urban land			Time of estimation	Dataset abbreviation	Citation
	Area (km^2)	% of total land area (%)	% of total land area* (%)			
Urban area		3.00**		2009	GHGUA	(Gamba and Herold 2009)
	3,506,830	2.38	2.64	1995	GRUMP	(CIESIN et al. 2011)
		2.00**		Circa 1996	WWCA	(O'Meara 1999)
	2,470,000	1.68	1.86	1985	GAULA	(Douglas 1994)
Built-up area	711,770 ~	0.48 ~	0.54 ~	2010	GULC2010	(Angel et al. 2011)
	869,358	0.59	0.65			
	657,000	0.45	0.49	Circa 2001–2002	MOD500	(Schneider et al. 2009, 2010)
Impervious surface	595,971	0.40	0.45	2010	IMPSA2010	(Elvidge et al. 2010; Sutton et al. 2010)

* Total land area excluded Antarctica and Greenland

** Only the percentage of urban land was published

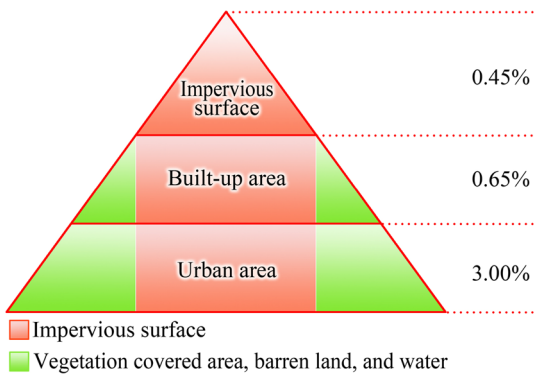

Fig. 1 A hierarchy of urban land definitions: urban area, built-up area, and impervious surface area. The numbers represent the best available estimates of the global urban land area around 2010, corresponding to each definition (see Table 2 for details). Antarctica and Greenland were excluded in calculating the percentage of the global urban land

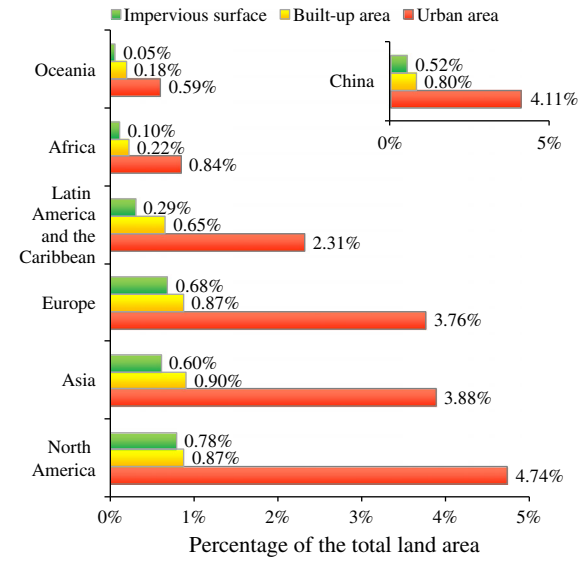

Fig. 2 Comparison of world regions in terms of their percentage of urban land based on the hierarchical system of definitions. The *inset* shows the percentage of urban land in China. The urban area was obtained from GRUMP (CIESIN 2011), the built-up area was derived from the high projection of GULC2010 (Angel et al. 2011), and the area of impervious surface was calculated using IMPSA2010 (Elvidge et al. 2010; Sutton et al. 2010). Greenland was excluded in the calculation of the percentage of urban land for North America

0.7–0.9 million km^2 (or 0.49–0.65 % of the global land area), according to the MOD500 dataset which has a spatial resolution of 500 m (Potere et al. 2009; Schneider et al. 2009, 2010) and the GULC2010 dataset which is an updated product of MOD500 (Angel et al. 2011). The total amount of "impervious surface" of the world was about 0.6 million km^2 (or 0.45 % of the global land area), according to Elvidge et al. (2010) and Sutton et al. (2010).

At the continental (or regional) scale, urban land estimates using the three different definitions also vary (Fig. 2). In 1995, the "urban area" was 4.74 % of the total land area in North America, 3–4 % in Asia and Europe, 2–3 % in Latin America and the Caribbean, and 0.5–1 % in Africa and Oceania. In 2010, the

World's region	Ratio of urban area to built-up area	Ratio of built-up area to impervious surface area	Ratio of urban area to impervious surface area
North America	5.45	1.12	6.08
Europe	4.32	1.28	5.53
Asia	4.31	1.50	6.47
Africa	3.82	2.20	8.40
Latin America & Caribbean	3.55	2.24	7.97
Oceania	3.28	3.60	11.80
World	**4.62**	**1.44**	**6.67**
China	5.14	1.54	7.90

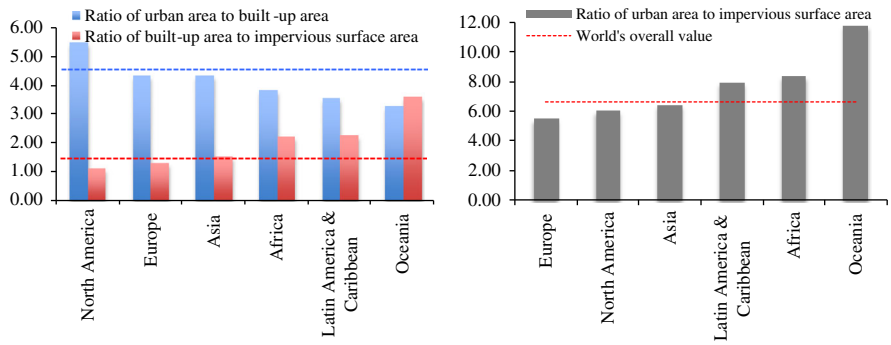

Fig. 3 Comparison of world regions in terms of the ratio of urban area to built-up area, the ratio of built-up area to impervious surface area, and the ratio of urban area to impervious surface area (see Fig. 2 for data sources). The *dashed lines* denote the overall value for the entire world. As an example of a nation state, China's numbers are listed in the table above the figure

"built-up area" was 0.8–0.9 % for North America, Asia, and Europe, 0.65 % for Latin America and the Caribbean, and circa 0.2 % for Africa and Oceania. The impervious surface area was 0.6–0.8 % in North America, Asia, and Europe, about 0.3 % in Latin America and the Caribbean, and 0.05–0.1 % in Africa and Oceania. At the national level, we took China as an example, and the results also showed a similar pattern in terms of the differences among the estimates of urban land area using the three definitions (Fig. 2). Except for the urban area (4.11 %), both the built-up area (0.80 %) and impervious surface area (0.52 %) for China were still smaller than those for Asia.

Overall, at the national, continental, and global scales, the difference between urban area and built-up area was much larger than the difference between built-up area and impervious surface area for all the cases examined except for Oceania (Fig. 3). For the world's regions, larger ratios of urban area to built-up area (UA/BUA) consistently correspond to lower ratios of built-up area to impervious surface area (BUA/ISA). North America had the highest UA/BUA and the lowest BUA/ISA, whereas Oceania had the lowest UA/BUA and the highest BUA/ISA. The ascending order by UA/BUA and the descending order by BUA/ISA turned out to be exactly the same (Fig. 3). The ratio of urban area to impervious surface area (UA/ISA) was also able to differentiate the more urbanized regions from those less urbanized, showing a similar pattern to that of BUA/ISA. In this case, however, the sequential rankings of the world regions were different, with Europe and North America switching places as the first and the second (Fig. 3). In terms of the values of these ratios, China fell between North America and Europe according to UA/BUA and between Europe and Asia according to BUA/ISA, but China's UA/ISA ratio was much higher the overall value of Asia and close to that of Latin America and Caribbean region (Fig. 3).

Concluding remarks

Definitional hierarchy—clarifying confusion and enhancing understanding

We have demonstrated that the definitional hierarchy of urban land proposed here enables us to clearly

address the question of how much of the world's land has been urbanized. This hierarchical framework can be used equally effectively on the local, regional, and global scales. When the literature states that the areal percentage of global urban land is between 2 and 3 % (e.g., Gamba and Herold 2009; CIESIN et al. 2011), it fits the definition of "urban area". However, the global built-up area is substantially smaller (about 0.65 % in 2010), and the global impervious surface area is much smaller (about 0.45 % in 2010). This general trend holds true at the regional and national scales.

The hierarchy of three urban land definitions can also help better understand and assess environmental and socioeconomic impacts of urbanization because they each have distinct physical meanings. For example, much of an urban area is not covered by concrete and asphalt or packed with people, but this may well be true for a built-up area. Large green spaces may frequently exist in an urban area, but are rare or nil in a built-up area. The average intensity of human-environment interactions per unit of space is expected higher in a built-up area than in an urban area if other conditions are similar. Impervious surfaces, by definition, are covered by materials such as concrete and asphalt, and are the culprit for the urban heat island (Buyantuyev and Wu 2010; Connors et al. 2013; Myint et al. 2013; Zhou et al. 2014). Yet the effects of the urban heat island can be mitigated by properly planning and designing the landscape of built-up areas and urban areas. Thus, differentiating the three urban land definitions should help improve the clarity of our communication, and more accurately understand the biophysical and socioeconomic ramifications of urbanization.

Improving data quality and updating estimates

Regardless of data-related problems, using this hierarchy of definitions can avoid the existing confusion on the spatial extent of urbanization of and across the world. However, the accuracy of the current estimates of urban land area at both the global and regional scales still needs improvements in several aspects. First, the estimates of the global urban area made more than a decade ago (Douglas 1994; CIESIN et al. 2011) need to be updated because the number and boundaries of administrative units in some countries and regions have changed since then. Second, GULC2010, the latest estimation of the global built-up area, was produced using the same changing rate of population density around the world without consideration of the regional differences of social and economic situations (Angel et al. 2011). As a result, the amount of urban area might be overestimated for some regions, but underestimated for some others. For the unique global impervious surface data, impervious surfaces in urban areas and rural areas were not distinguished, so the estimated urban impervious surface area were overestimated (Elvidge et al. 2010; Sutton et al. 2010).

In addition, several factors may affect the numerical values of the three kinds of urban land area. This is nothing new, of course. Urban land area is simply a landscape metric, and just like many other landscape metrics its value is affected by scale (resolution or grain size, extent or map size, and sampling window size) and data accuracy. Particularly for built-up area, the choice of the basic spatial unit to compute the percentage of human-constructed land cover may substantially influence the estimated overall built-up area in a geographical region. Problems of this sort now are well-recognized in landscape and geospatial studies (Woodcock and Strahler 1987; Moody and Woodcock 1995; Wickham and Riitters 1995; Wu 2004, 2007; Shao and Wu 2008; Wu 2013b).

New urbanization indicators?

Interestingly, this study suggests that the ratios of the three urban land measures (UA/BUA, BUA/ISA, and UA/ISA) may be used as indicators for the level of urban development or some aspects of it. For instance, higher ratios of UA/ISA or UA/BUA may correspond to relatively higher percentages of open space within an urban area, possibly as a result of rapid urban expansion or urban annexation. Higher ratios of BUA/ISA may be indicative of urban areas dominated by low-density development, whereas low ratios of BUA/ISA may be correlated with more compact urban development. These are speculations at this point, and a number of questions remain to be addressed. For example, what do the intriguing patterns in Fig. 3 really mean in terms of urban development, environmental settings, and socioeconomic conditions? How do these patterns change across different scales (e.g., the county, provincial, or national level)? These are certainly questions that deserve further studies in the future. These ratios may be helpful for understanding the relationship among the impervious surface area,

built-up area, and broader urban area in a geographic region, as well as the similarities and differences in this relationship among different regions.

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