Monitoring 25 years of Land Use Efficiency in 10,000 Urban Centers: perspectives from the Global Human Settlements Layer

Michele Melchiorri
Analyst, Piksel (corresponding author)
michele.melchiorri@piksel.com
Via Breda 176
Milano, Italy 20126

Aneta J. Florczyk, European Commission Directorate General Joint Research Centre;
Christina Corbane, European Commission Directorate General Joint Research Centre;
Marcello Schiavina, European Commission Directorate General Joint Research Centre;
Martino Pesaresi, European Commission Directorate General Joint Research Centre.

The surge of sustainable urban development challenges at the world polity level during the Post-2015 Development Agenda process and the consolidation of specific goals and indicators for sustainable urban development leave no room for gaps in urbanization knowledge, information and reporting.
SDG 11 aspires to "Make cities and human settlements inclusive, safe, resilient and sustainable" and the salience of an explicit urban goal necessarily stems from the recognition that human society has become predominantly urban. The understanding of the process of urbanization and the capacity to monitor the progress in meeting the SDGs require a wealth of open, reliable, local but globally comparable data and a fully-fledged Data Revolution. New sources of information, like Earth Observation, Big-data and gridded geospatial data can offer support to transformative policies with a new generation of information that are: planetary and multi-temporal in coverage, fine scale in detail, open and free in access.
It is in the above framework and auspices that the European Commission - Joint Research Centre has developed a suite of (open and free) data and tools named Global Human Settlement Layer (GHSL). The GHSL maps the human presence on Earth sourcing information back to 1975 and up until 2015 delineating built-up areas, population distribution and classifying settlement typologies.
The GHSL information on the progressive expansion of built up areas in cities and their demographic changes is a suitable baseline data to quantify the Land Use Efficiency, listed as indicator for SDG 11 (11.3).
In the paper, we present the profile of the LUE on the universe of cities across circa 10,000 Urban Centers in the year 2015, and its change since 1990. We demonstrate how urban areas and human settlement develop with diverse trajectories by exploiting land with different degrees of efficiency. With our results we draw three main propositions: first that innovative open data derived from Earth observation make it possible to estimate LUE for the entire planet despite the tier 2 nature of SDG 11.3.1; second that the LUE present formulation is substantially subject to path dependency in quantifying the efficiency of new development anchoring it to past trajectories; third that LUE indicator should be interpreted in combination with another proxy indicator like the Abstract Achieved Population Density in Expansion Areas, which we propose along our argumentation.

I. Introduction

The settlement space is among the key markers of human life on Earth since ancient history, and the relationship between settlements and development of civilizations is very strong[1]. Earth population exceeds 7 billion and just portions of the planet remain far from human settlements or artificial land[2], so the additional 1.26 billion people projected to inhabit the globe by 2030[3] pose a serious challenge to the use of natural resources. The human load on the planet and the resulting modifications have gained resonance in research and policy response especially after the Earth Summit in 1992 (which gathered United Nations Member States to condense a global agenda on –sustainable-development). At dawn of the XXI century, the degree of human impact on the planet is deemed so high that some scientists suggest that Earth has moved to a new geological era, the *Anthropocene*[4].

In the Anthropocene, the interaction between humans and the Earth ecosystem is transformative and degradative[5]. The main impacts affect critical natural resources like air, water and soil[6]. Urbanization, due to the intensity of its dynamics, and its planetary reach has become a characterizing process of the Anthropocene making cities a key player in the consumption of natural resources[7].
As urban expansion retains a dual essence, one demographic and the other spatial, it is key to understand the interdependence between these two natures: namely between spatial expansion over land and demographic change.

The 2030 Development Agenda devotes to land a specific Goal (SDG 15 "Life on Land"). Goal 15 is rich of interlinkages with other Goals, especially including: human development (SDGs 1, 2, 3, and 6), terrestrial ecosystem protection (6, 12, and 14), sustainable activities and economic growth (1, 8, 9, 11, and 12).
In particular, this contribution focuses on the interplay between land consumption and sustainable urban development. This interplay is taken into account by the SDG 11 ("Make cities and human settlements inclusive, safe, resilient and sustainable") and formalized by the SDG indicator 11.3.1 that aspires to monitor the "Ratio of land consumption rate to population growth rate". The Inter-Agency Expert Group on SDG Indicators classified indicator 11.3.1 as tier 2. A globally agreed methodology exists, but data are not available or not regularly updated.

In the paper we propose the use of open and free data to estimate the Land Use Efficiency (LUE) indicator for the period 1990-2015. In doing so we rely on the Global Human Settlements Layer (GHSL), a framework of data and tools developed at the European Commission Directorate General Joint Research Centre. With the GHSL it was possible to source information on the spatial extent of built-up areas and the resident population of human settlements that are the key input to quantify the SDG LUE indicator. With the

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[1] Gary M. Feinman, "Settlement and Landscape Archaeology," in *International Encyclopedia of the Social & Behavioral Sciences* (Elsevier, 2015), 654–58, https://doi.org/10.1016/B978-0-08-097086-8.13041-7.
[2] Aneta J. Florczyk, et. al, "Settlement Space map: mapping the Earth surface in vicinity of built-up areas" (submitted) in *International Journal of Digital Earth* (Taylor and Francis, 2018).
[3] United Nations, Department of Economic and Social Affairs, Population Division, "World Urbanization Prospects: The 2018 Revision," 2018.
[4] Timothy Beach et al., "The View from the 'Anthropocene': New Perspectives in Human-Induced Environmental Change," *Anthropocene* 15 (September 2016): 1–2, https://doi.org/10.1016/j.ancene.2016.09.004.
[5] P. M. Vitousek, "Human Domination of Earth's Ecosystems," Science 277, no. 5325 (July 25, 1997): 494–99, https://doi.org/10.1126/science.277.5325.494.
[6] Frank Biermann et al., "Down to Earth: Contextualizing the Anthropocene," Global Environmental Change 39 (July 2016): 341–50, https://doi.org/10.1016/j.gloenvcha.2015.11.004.
[7] Stephanie Pincetl, "Cities in the Age of the Anthropocene: Climate Change Agents and the Potential for Mitigation," Anthropocene 20 (December 2017): 74–82, https://doi.org/10.1016/j.ancene.2017.08.001.

information derived from Earth Observation and population census, the GHSL could serve to fill gaps in data and so to support the LUE estimation.
Through the paper, we formulate 3 propositions:

- Using GHSL open and free multi-temporal data *it has been possible to quantify the* LUE at the city level using ready available and open data. We demonstrate this with a comprehensive global map;

- We suggest to maintain the LUE result value (dimensionless) as a proxy of a development trajectory, and to support it with the *estimation of the abstract population density per unit of spatial expansion* that more closely capture the characteristics of the socio-spatial development. We demonstrate the above showing the variety population density achieved in areas of urban centers expansion across regions of the world.

- The present internationally *agreed LUE formulation is substantially subject to path dependency in quantifying the efficiency of new development anchoring it to past trajectories*, this feature is rooted in the mathematical formulation.

GHSL data have been applied to estimate the an adapted formulation of the LUE on the basis of built-up areas per capita change in delimited spatial units using the GHSL Land Use Efficiency Tool[8]. In this contribution, we instead quantify the LUE indicator with the internationally agreed methodology in all urban centers on Earth.

II. Methods and Materials

The tier 2 nature of SDG 11.3.1 offers an internationally agreed methodology to estimate the indicator, and presses to identify sources of data that provide information for at least half the countries (and representing half the population) of a region of the world to enable monitoring of progress made towards achieving SDG 11. The methodology for SDG 11.3.1 is established and referenced in the SDG indicators Metadata Repository managed by UNDESA[9]. LUE monitors the "Ratio of land consumption rate to population growth rate" and it is entrusted to quantify the wise use of land consequence of urban expansion pressures[10] (demographic and economic ones[11]).
To estimate LUE, first it is necessary to quantify the rate of land consumption (LCR) and the population growth rate (PGR) in a given spatial unit over a time span. The two rates (LCR and PGR) are computed as follows:

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[8] https://ghsl.jrc.ec.europa.eu/tools.php
Christina Corbane et al., "Assessment of Land Use Efficiency Using GHSL Derived Indicators," in Atlas of the Human Planet 2016 (Publications Office of the European Union, 2016), 82–83.
[9] https://unstats.un.org/sdgs/metadata
[10] Annemarie Schneider and Curtis E. Woodcock, "Compact, Dispersed, Fragmented, Extensive? A Comparison of Urban Growth in Twenty-Five Global Cities Using Remotely Sensed Data, Pattern Metrics and Census Information," *Urban Studies* 45, no. 3 (March 2008): 659–92, https://doi.org/10.1177/0042098007087340.
[11] Remi Jedwab, Luc Christiaensen, and Marina Gindelsky, "Demography, Urbanization and Development: Rural Push, Urban Pull and … Urban Push?," *Journal of Urban Economics* 98 (March 2017): 6–16, https://doi.org/10.1016/j.jue.2015.09.002; Anthony J. Venables, "Breaking into Tradables: Urban Form and Urban Function in a Developing City," *Journal of Urban Economics* 98 (March 2017): 88–97, https://doi.org/10.1016/j.jue.2017.01.002; Edward Glaeser and J. Vernon Henderson, "Urban Economics for the Developing World: An Introduction," *Journal of Urban Economics* 98 (March 2017): 1–5, https://doi.org/10.1016/j.jue.2017.01.003.

$$LCR = \frac{LN\ ({}^{Urb_{t+n}}/_{Urb_t})}{y} \qquad PGR = \frac{LN\ ({}^{Pop_{t+n}}/_{Pop_t})}{y} \tag{1}$$

where Urb_t and Urb_{t+n} reflect the total areal extent of the land consumed (extent of the human settlement) at the initial reference year *(t)* and at the final reference year *(t+n)* respectively, Pop_t and Pop_{t+n} input the total population of the spatial unit at the initial reference year *(t)* and at the final reference year *(t+n)* respectively, and *y* is the number of years between *t* and *t+n*. The estimate of the ratio of land consumption rate to population growth rate (LCRPGR), is obtained with:

The estimate of the ratio of land consumption rate to population growth rate (LCRPGR), is obtained with:

$$LUE\ (LCRPGR)\ = \frac{LCR}{PGR} \tag{2}$$

The classification of regions of the world is based on the aggregation of countries from the Global Administrative Map (V2.8[12]) following the categories of the UN World Urbanization Prospects 2018. The extraction of statistics on built-up areas and population was implemented in Geographic Information System environment (ArcGIS) through zonal statistics operations.

In addition to the LUE indicator, it is proposed to consider an additional metric, *the Abstract Achieved Population Density in Expansion Areas* (AAPDEA). AAPDEA is computed on the basis of the absolute difference between the spatial expansion of the settlement and the change in population in the same spatial unit, as follows:

$$AAPDEA\ (number\ of\ people\ per\ km^2) = \frac{Pop_{t+n} - Pop_t}{Urb_{t+n} - Urb_t} \tag{3}$$

The LUE formulation requires multi-temporal data (at t and t+n) for the spatial extent of the settlement, and the resident population. Data to quantify LCR are scarcely available as the definition of consumed land is disputable, and data to quantify PGR are often not directly available for the spatial unit of interest (i.e. subnational level or cities). To quantify the LUE we therefore adopted a new generation of data, derived from EO as this information source sets out as key contributor to provide data to support SDG monitoring[13]. In the specific case of the SDG 11.3.1 the GHSL is the only dataset that covers all the globe supplying multi-temporal open data on the spatial extent of settlement and the resident population. In the GHSL framework the information on the spatial footprint of human settlement is taken from the GHS-BUILT layer that maps the density of built-up areas (defined as roofed surfaces) at a spatial resolution of 30m extracting the information from Landsat imagery[14]. The demographic information is contained in the GHS-POP that splits the land surface in 1km grid cells to report the population density for each. Population is mapped with dasymetric disaggregation on the basis of built-up presence and corresponding density[15]. From the distribution of built-up areas and the modelled resident population, the GHSL was used to support the "*Harmonised Definition of Cities and Settlements*" (currently developed by the European Commission and to which the

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[12] https://gadm.org/index.html

[13] Katherine Anderson et al., "Earth Observation in Service of the 2030 Agenda for Sustainable Development," *Geo-Spatial Information Science* 20, no. 2 (April 3, 2017): 77–96, https://doi.org/10.1080/10095020.2017.1333230.

[14] Martino Pesaresi et al., "Operating Procedure for the Production of the Global Human Settlement Layer from Landsat Data of the Epochs 1975, 1990, 2000, and 2014," JRC Technical Report (Ispra, Italy: Publications Office of the European Union, 2016), http://publications.jrc.ec.europa.eu/repository/handle/JRC97705.

[15] Sergio Freire et al., "Combining GHSL and GPW to Improve Global Population Mapping," in *Geoscience and Remote Sensing Symposium (IGARSS), 2015 IEEE International*, 2015.

Organisation for Economic Cooperation and Development –OECD, the World Bank, the Food and Agriculture Organization -FAO, and the United Nations Settlement Programme –UN-Habitat, voluntarily committed) and this resulted in the GHS-SMOD that is the third GHSL layer that maps settlements in three typologies *Urban Centres*, *Urban Clusters* and *Rural Areas* according to a people based definition (by applying a population density and total threshold)[16]. In this research the delineation and definition urban areas is the one of the *Urban Centres* class in the GHS-SMOD. This allows to identify cities and extract related statistics in a harmonized way across space and time to make comparisons possible. JRC released in 2016, at Habitat III the suite of tools and data that include multi-temporal layers like GHS-BUILT[17], GHS-POP[18] and GHS-SMOD[19] grids. In this work, we use the new version of these data package shared in the framework of the Group on Earth Observations Human Planet Initiative[20]. The initiative is committed to developing a new generation of measurements and information product that provide new scientific evidence and comprehensive understanding of the human presence on the planet that cans support global policy processes with agreed, actionable and goal-driven metrics. Our database included the ~10,000 urban centers mapped in the GHS-SMOD for epoch 2015.

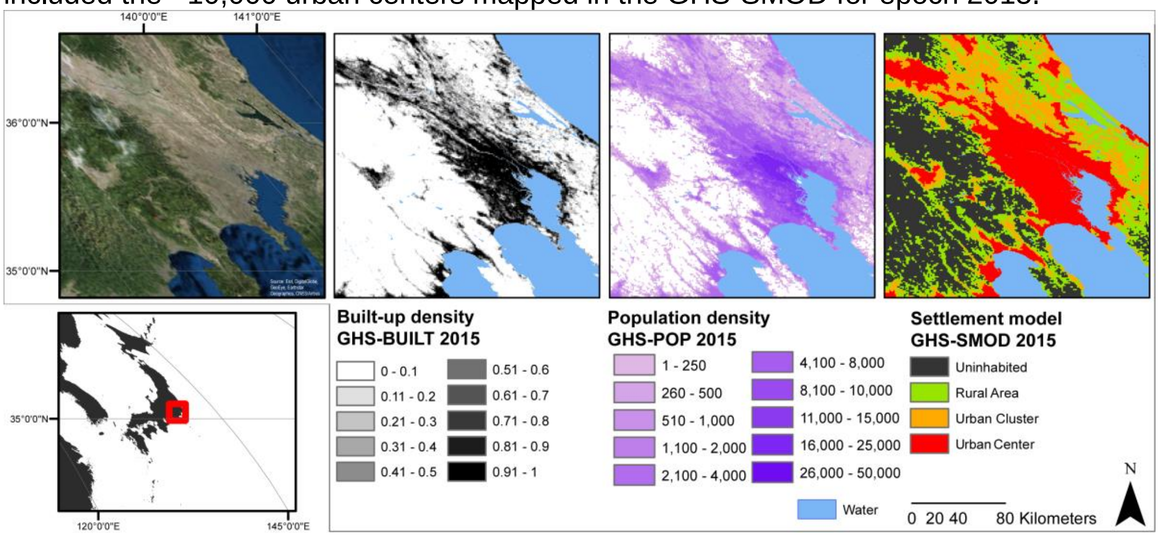

Figure 1 example of GHSL data, GHS-BUILT, GHS-POP, GHS-SMOD displayed at 1km spatial resolution in the area of Tokyo (Japan) and compared to the imagery base map (right).

III. Results

LUE has been estimated in circa 10,000 urban centers. As comprehensive overview of the SDG 11.3.1 quantified with GHSL data over the 25 years between 1990 and 2015 it results that urban centers follow a development trajectory in which the rate of spatial expansion prevailed (slightly) on that of population growth in the period 1990-2000 (LUE=1.05), while the rate of population growth prevailed over that of spatial expansion in the period 2000-2015 (LUE=0.45). Considering the full period, urban centers developed with a LUE equivalent to 0.72. In absolute terms urban centers expanded over a land

[16] Lewis Dijkstra and Hugo Poelman, "A Harmonised Definition of Cities and Rural Areas: The New Degree of Urbanisation" (Publications Office of the European Union, 2014).
[17] https://ghsl.jrc.ec.europa.eu/ghs_bu.php
[18] https://ghsl.jrc.ec.europa.eu/ghs_pop.php
[19] https://ghsl.jrc.ec.europa.eu/ghs_smod.php
[20] https://www.earthobservations.org/activity.php?id=119

surface equivalent to almost 67,800 km^2 (approximately the surface of Ireland) to settle almost 1.1 billion new people (almost the population of India in 2015).

III.I LUE in 10,000 urban centers

To synthetically report on the LUE trajectories of this vast dataset, we grouped centers by classes of LUE change in the ranges LUE≤-1; -1<LUE≤0; 0<LUE≤1; 1<LUE≤2; LUE>2. Figure 2 below displays the geographical distribution of urban centers and their related LUE class (1990-2015) and charts comparing the relative distribution of centers in the corresponding LUE classes. It emerges that 13% of the centers in the globe developed between 1990 and 2015 with a substantially negative LUE value (<-1) in particular in countries in central and western Europe, central China and south India. Values in the range -1<LUE≤0 are accounted in 6% of centers of the globe, this share reaches 21% in Europe (especially in Eastern Europe and Russia), and 18% in Asia (mainly Japan). Most frequent LUE class across the globe is the one ranging 0<LUE≤1 (39% of the centers in the dataset). On a regional basis, this class is representative of 65% of the centers in Africa, more than half the ones in Latin America and the Caribbean, 39% the centers in Oceania, and almost 1/3 the ones in Asia and Europe. The class 1<LUE≤2 includes 20% of the centers in the globe, but almost 1/3 the ones in Latin America and the Caribbean, ¼ the ones in Northern America and 22% of the ones in Africa. The last class (LUE>2) globally accounts 22% of the centers, this share increases in Asia –31% especially including centers in India and north-east and south China.

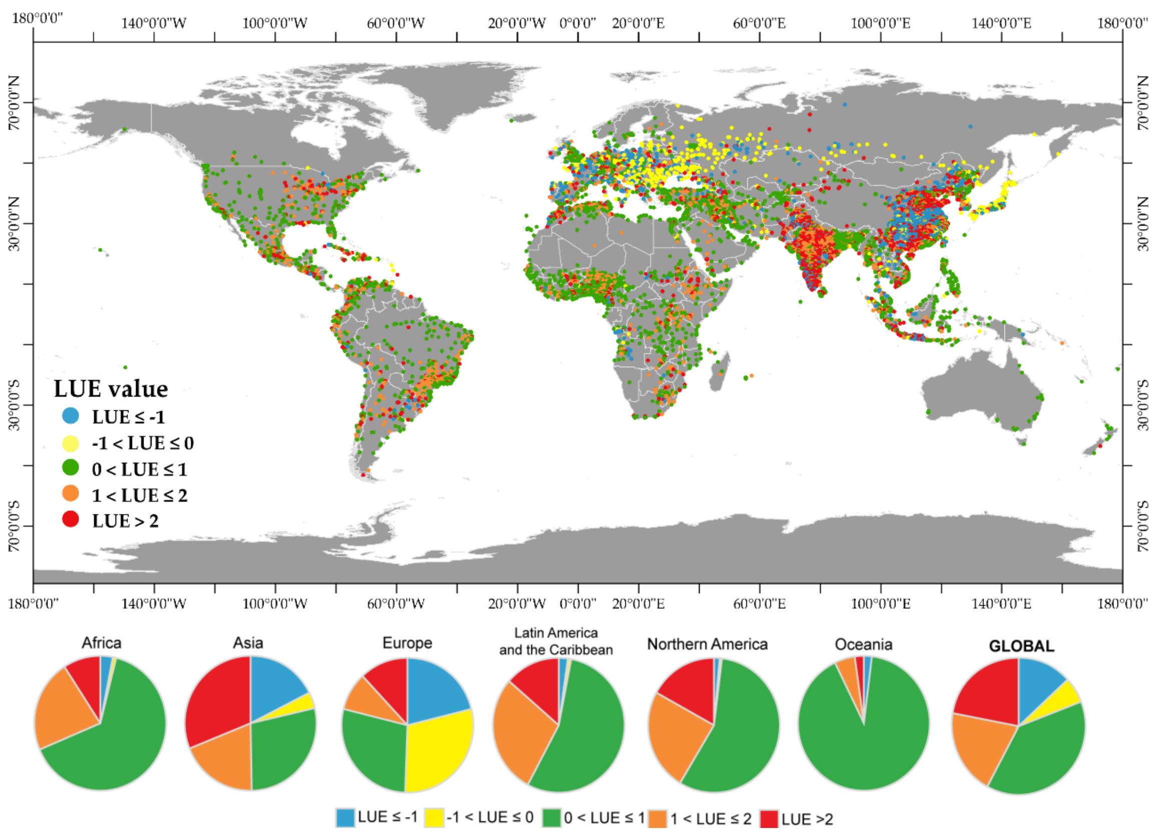

Figure 2. Comprehensive visualization of the LUE value in the circa 10,000 urban centers and relative LUE computed on LCR and PGR in the period 1990-2015.

III.II LUE dynamics: abstract achieved densities in areas of expansion

In order to grasp the trajectories of sustainable urban development across cities of the world, it is necessary to go beyond the dimensionless LUE value and to consider indexes with an explicit spatial metrics. The "AAPDEA" quantifies the abstract population density per unit of areal expansion (inhabitants per km^2). In Figure 3 we compare the abstract number of inhabitants that each km^2 of expansion of urban centers between 1990 and 2015 would host. As global average 15,800 people are settled in each km^2 of urban expansion. This global value is very diverse across regions. It is almost three times higher in centers in Africa, where with each km^2 of urban expansion more than 40,000 people are accommodated. In centers in Northern America and Europe each km^2 of urban expansion would host approximately less than 3,000 people.

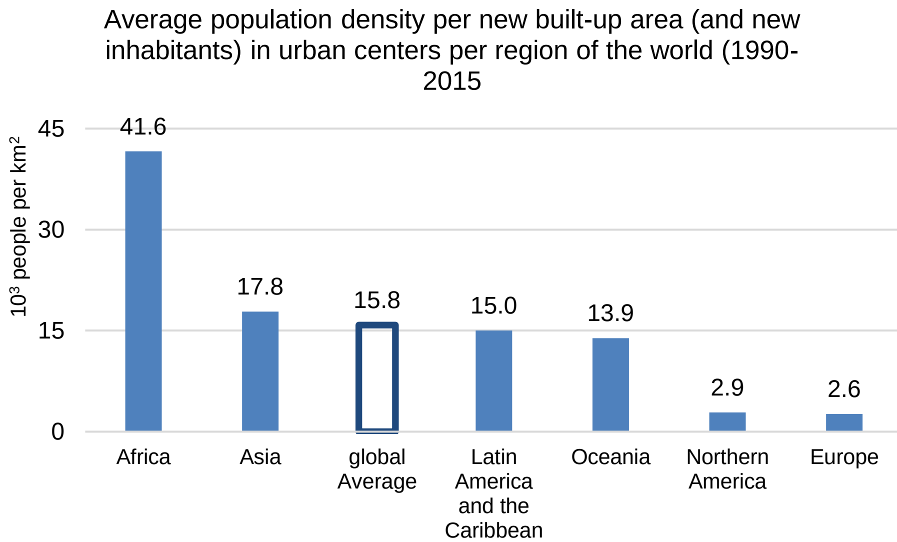

Figure 3 regional comparison of AAPDEA values

Making the example of the two America regions, we report about a development dynamic that the LUE indicator is not capable to capture.

The LUE is 0.9 and 0.8 respectively in Latin America and the Caribbean and Northern America. By LUE definition, the value results into higher efficiency in urban centers expansion in Northern America (LUE close above 0 and below 1). However, the abstract population density in areas of expansion (AAPDEA), in Northern America is equivalent to 2,870 people settled per each km^2 of land expansion of an urban center. In Latin America and the Caribbean, for each km^2 of land expansion of an urban center, 15,011 people were potentially settled. Indeed, the values generated through this metrics is reflected in the total land consumption in the regions, where for the almost 38 million new urban centers inhabitants in Northern America, an overall 13,200 km^2 of land was consumed. In Latin America, urban centers have expanded by 7,000 km^2 to accommodate 105 million people in total.

IV. Discussion

The results of our analysis have displayed through the LUE indicator the trajectories of development of human settlements in space and demographic terms between 1990 and 2015. In the following paragraphs, we reflect on a simulation of the AAPDEA metrics for two regions of the world, then we shed light on some caveats of the LUE indicator formulation Last, we list some of the limitations of the adopted materials and methods.

IV.I Dimensionless versus spatial metrics to quantify LUE

It was earlier presented how the LUE indicator and AAPDEA are interdependent. LUE is therefore considered to be a useful proxy indicator but insufficient as metric for comparing development trajectories. As noted in the previous section a highly efficient trajectory of development in one case study spatial unit (low LUE value) might be associated with substantially lower AAPDEA compared to comparable LUE values in other spatial units. In fact, to accommodate the almost 40 million people new in Northern American centers between 1990 and 2015, the centers would have expanded only 1/5 the times they actually expanded (about 2,500 km^2 instead of about 13,000 km^2) if they expanded at the AAPDEA of Latin America and the Caribbean. Similarly, if Latin American and Caribbean centers would expand at Northern American densities, to accommodate 105 million people they consume almost 37,000 $km^2$of land (while they consumed 7,000 km^2). These figures are captured by LUE values of 0.9 for Northern America and 0.8 for Latin America and the Caribbean. In the comparison of the sole LUE value Northern centers would look more efficient than the ones in the other region. The spatially explicit metric (AAPDEA) shows that it is not certainly so in absolute spatial terms.

In the mathematical formulation of the LUE indicator, it is not analyzed how efficient in absolute terms the trajectory of development actually is, instead it is observed whether the trajectory is continued as is, curbed towards population densification ($0<LUE<1$), or diverts towards more intense spatial expansion ($LUE>1$). No observation is therefore provided on the initial condition of land consumption and population density, this make the comparison of the LUE value across different spatial units implausible, or at least not representative.

IV.II Path dependency and LUE awareness

By anchoring LUE values to past development trajectories the present LUE formulation seems to be bounded to path dependency, introducing a normative connotation based on historical settings[21].

This framework, treats as equally efficient in the use of land settlements that while developing at equal LUE values achieve substantially different AAPDEA. Examples of this proposition include cases of settlements developing at LUE=1, that therefore continue developing maintaining the land consumed per new inhabitant equal to the built-up area per capita per inhabitant in the initial year. By comparing LUE value, it was noted above that the variety of AAPDEA value is vast even if LUE is similar.

In a sustainable urban development perspective, the variety of planning tools and access to technology may nudge conservative development control (high AAPDEA) for territories with a tradition of high land consumption per inhabitant to pursue low LUE values (i.e. greater than 0 and below 1 to populate areas of new expansion more than the existing urban center). Instead promoting the increase of built-up per capita (increase LUE values) in developing countries where settlements might be excessively compact and lacking basic services and public spaces.

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[21] Adrian Kay, “A Critique of the Use of Path Dependency in Policy Studies,” *Public Administration* 83, no. 3 (August 2005): 553–71, https://doi.org/10.1111/j.0033-3298.2005.00462.x.

IV.III Filling the data gap with open data

Last, it is fair to list a number of caveats related to the estimation of LUE in our research. The tier 2 nature of SDG 11.3.1 for which data are not largely available or not regularly updated forced to identify alternative data source to quantify the indicator. Using the GHSL it was possible to source fine scale, global coverage, multi-temporal data on the spatial extent and population for each 1km grid cell on the landmass. The GHSL is produced from the best open data available to map built-up areas (Landsat imagery) and GPW4 population estimates[22]. The LUE estimation may be affected by omission and commission error in the detection of built-up areas (biasing LCR) or in the population disaggregation due to inconsistencies in the census estimates and their spatialization (distorting PGR).

V. Conclusion

In this paper, we presented the estimate of the Land Use Efficiency, listed as tier 2 indicator for the Sustainable Development Goal 11 (“Make cities and human settlements inclusive, safe, resilient and sustainable”). The “Ratio of land consumption rate to population growth rate” (SDG 11.3.1), is currently classified as tier 2 indicator as a globally agreed methodology exists, but data are not available or not regularly updated.

The GHSL supplied open data on the spatial distribution of built-up areas, population and settlement typologies at the corresponding year 1990, 2000, and 2015. With the GHSL we estimated the global LUE between 1990 and 2015 bridging the gap between a tier 2 indicator nature and the estimation of the indicator for urban centers across the whole globe.

The results of our analysis demonstrate that urban centers developed more in space than in population in the period 1990-2000 and more in population than in space between 2000 and 2015. The 25 years aggregated LUE shows that population in urban centers has grown at faster rates compared to spatial expansion. This is in principle justified by the urban nature, where population densities are high.

By observing the abstract achieved density in expansion areas, we demonstrated however that population density in expansion areas varies greatly across regions of the world. In practice, regions that develop at a certain LUE value may achieve just a fraction of population densities of other regions that develop at the same LUE value or even at a more efficient one. Our results also demonstrate that this characteristic of the LUE indicator is rooted in the mathematical formulation of the indicator. Our study sheds light on the path dependency nature of the indicator and therefore we question whether the LUE indicator, taken as dimensionless metric is fully capable to capture the relationship between the rate of spatial expansion and that of population.

[22] http://sedac.ciesin.columbia.edu/data/collection/gpw-v4