CEOS
Committee on Earth Observation Satellites

SUSTAINABLE DEVELOPMENT GOALS

EO SUPPORT SHEET

SDG Indicator 11.3.1

Ratio of land consumption rate to population growth rate

11 SUSTAINABLE CITIES AND COMMUNITIES

December 2024

Contributors:

- Martyn Clark, GEO Secretariat, Switzerland
- Corena Pincham, NASA, USA

Table of Contents

KEY CHANGES IN THE 2024 UPDATE

1. **Indicator Classification Change:** Reclassified from TIER-II to TIER-I, indicating improved data availability for more than 50% of countries and population in every relevant region

2. **New Datasets Added:**
    - WSF 2019 and planned releases for 2025 (WSF2019 imperviousness, WSF population, WSF tracker)
    - Google's Open Buildings 2.5D Temporal Dataset
    - Updated GHSL releases through Copernicus programme (2022-2024-2026)

3. **Updated Methods & Tools:**
    - Enhanced guidance for using cloud computing platforms (AWS, Google Earth Engine)
    - Additional validation methodologies and requirements
    - Expanded guidance on using commercial satellite data

1. DETAILS OF SDG INDICATOR 11.31

INDICATOR	11.3.1 Ratio of land consumption rate to population growth rate.
Target	11.3 By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.
Custodian Agency	United Nations Human Settlements Programme (UN-Habitat) **TIER** II

Objectives

The indicator aims at monitoring and measuring urban land-use efficiency by comparing the urban land consumption rate with the population growth rate on similar temporal and spatial scales. This indicator requires defining two components: population growth and land consumption rate to derive the ratio of land consumption rate to population growth rate (LCRPGR). The formula can be summarized as follows:

$$LCRPGR = \frac{\text{Annual Land Consumption rate}}{\text{Annual Population growth rate}} \quad \text{[eq 1.]}$$

Practically, equation 1 is computed in a two-step process involving the data collection and estimation of population growth and land consumption respectively. The land consumption rate is defined as the rate at which urbanized land or land occupied by an urban area changes during a period of time (usually one year), expressed as a percentage of the land occupied by the urban area at the start of that time.

Baseline and Reporting

According to the metadata for this indicator, UN-Habitat and partners have been creating a repository of 11.3.1 data using 1990 as the baseline year. Other repositories listed below provide data going back further. UN Habitat, however, encourages countries to compute the indicator as far as back as data is available and maintain the current/most recent year as the final reporting year. Reporting is repeated at regular intervals based on the input data resolution, with the most common cycles being 5 or 10 years. In particular, since the indicator relies on (historical) image analysis, the spatial resolution of imagery can significantly influence the frequency of data compilation, particularly where population estimates are also frequently undertaken. In some countries where very high resolution satellite imagery is available, annual measurements are possible. However, in some contexts significant differences in population growth and land consumption may not be observable over shorter timescales particularly where coarser satellite data products are used to derive land consumption rates.

Since December 2023, the indicator has been classified as TIER-I, meaning that the indicator is conceptually clear, has an established methodology as well as data availability for more than 50% of countries and of the population in every region where the indicator is relevant. The global metadata for SDG 11.3.1 (UN-Habitat) recommends use of the Degree of Urbanisation method — endorsed at the 51st session of the UN Statistical Commission — for delineation of cities/urban areas, which form the unit of analysis for the indicator.

The components of the indicator should be derived from national data on population growth and land consumption. Where national data is unavailable, several global datasets exist to allow these components to be determined. Examples include **population data** collected by CIESIN and modelled into grids by various organisations (see Gridded Population of the World, GHS-Pop, WorldPop, etc.)

and **land or built-up area data** from products such as the Global Human Settlement Layer (GHSL), World Settlement Footprint, Google's Open Buildings 2.5D Temporal Dataset, among others.

Some of these products have a continuing production calendar up to and beyond 2030, making them useful for continously monitoring the indicator. The GHSL framework for example provides data and tools developed from Earth Observation, census data, and volunteered geographic information that produces global maps of built-up areas, resident population, and settlement typologies for twelve epochs (1975- 2020 with a 5-year interval). The GHSL global open data is available and it will be updated through European Union Copernicus programme support and international partnership with biennial releases (2022-2024-2026). Other relevant datasets are listed below under the 'EO-based global datasets' section.

The method to compute the ratio of land consumption rate to population growth rate follows five broad steps:

1. Deciding on the analysis period/years,
2. Delineation of the urban area or city, which will act as the geographical scope for the analysis through the Degree of Urbanisation (DEGURBA) methodology,
3. Spatial analysis and computation of the land consumption rate,
4. Spatial analysis and computation of the population growth rate,
5. Computation of the ratio of land consumption rate to population growth rate, and Computation of recommended secondary indicators (for example, built-up area per capita, total change in built up area). See the indicator metadata for more information.

The Degree of Urbanisation method streamlines the process of defining the area of analysis consistently by applying population size and population density thresholds to classify the entire territory of a country along the urban-rural continuum. This method captures the full extent of a city, including the dense neighbourhoods beyond the boundary of the municipality. The Degree of Urbanisation can be used to calculate the indicator at the grid level, or for territorial units classified by Degree of Urbanisation typology.

The use of the DEGURBA methodology is also important as a workable method to delineate cities, urban and rural areas for international statistical comparisons. Countries are thus encouraged to adopt this approach, which will help them produce data that is comparable across urban areas within their territories, as well as with urban areas and cities in other countries. The Degree of Urbanisation can be easily applied with free software tools developed by the EU's Joint Research Centre.

Challenges The major challenge for this indicator lies in its interpretation. In each human settlement structure, there are many factors at play that make it more difficult to generalize the implication of a single LCRPGR value to sustainable urbanization. On the other hand, a value of one may not mean an optimal balance between spatial growth of urban areas and their populations, since it would imply new developments with every unit increase in population. To help explain the values of the indicator, two secondary indicators have been proposed, which use the same inputs as the core indicator: built up area per capita and total change in built up area.

Other limitations of the indicator include aggregating values at a national scale from different cities, which could easily get influced by zero or negative growth ; and, measuring the urban expansion by conurbations of two or more urban areas that are in close proximity – which can be resolved by use of the globally harmonized DEGURBA methodology.

The implementation of this indicator may also face technical and operational constraints, including: the need for consistent Earth Observation time series data, computing infrastructure for processing high-resolution imagery, specialized expertise in geospatial analysis, and established data sharing protocols between relevant national agencies. These technical requirements underscore the importance of capacity building and standardized methodological approaches to ensure reliable indicator monitoring.

See the metadata for more detailed exploration of limitations.

2. SATELLITE OBSERVATIONS

a) Satellite data requirements

SDG Requirement	Spatial Resolution	Measurement Type	Observation Frequency	Sampling Type	Comments	Mission Classes
SDG 11.3.1	10-500 m	Optical or Radar	Annual and sub-annual	Land Mask	UN-Habitat is the custodian agency, with support from partners/regional commissions. Suggests the Degree of Urbanisation method to independently delineate cities, urban, and rural areas; and the use of national produced and validated data for calculation. Metadata refer countries to the EO Toolkit for Sustainable Cities and Human Settlements to easily access and assess data of interest to compute indicator 11.3.1, where national data or capacities to produce it from openly accessible EO resources are limited.	1, 2, 3, 4

b) What data is currently available and relevant?

There is a range of satellite data sources which could be used within the SDG 11.3.1 indicator monitoring and reporting. Satellite imagery for the mapping of built-up areas can be obtained from public and freely accessible data collections as well as from commercial distributors. A summary of the available options is provided in the table below.

Sensor	Type	Spatial resolution	Temporal coverage / Revisit time	Data policy	Comment
Sentinel-1	SAR	10 m	From 2014 / At least every 12 days globally	Free and open	Limited historical data but the long-term continuity is secured under the Copernicus program.

Sentinel-2	Multi-spectral	10 m	From 2015 / Every 5 days globally	Free and open	Limited historical data but the long-term continuity is secured under the Copernicus program. Sensitive to clouds; useful imagery may be restricted in cloudy regions.
Landsat	Multi-spectral	30 m	Since 1984 / Every 16 days globally	Free and open	Long temporal coverage is invaluable for historic mapping and Landsat now available as a harmonised product covering all of the missions. However, 30-meter resolution is a drawback compared to the Sentinels. Sensitive to clouds; useful imagery may be restricted in cloudy regions.
Commercial	SAR and Multi-spectral	0.5 m - 2.5 m	Since ~2000/ New acquisitions (on demand); Historic imagery (depending on archive)	Proprietary/ Cost from 2.5 to 20 €/km2	Provides the highest level of detail but at expense of cost

c) Where to access EO Data?

Missions	Main source	Website
CORE MISSIONS		
Landsat	EarthExplorer	https://earthexplorer.usgs.gov/ Harmonized product: https://lpdaac.usgs.gov/data/get-started-data/collection-overview/missions/harmonized-landsat-sentinel-2-hls-overview/
Sentinel	Data and Information Access Services (DIAS) Or Conventional Data Hubs	https://www.copernicus.eu/en/access-data
OTHER DATASETS		
More datasets	NASA SEDAC	https://sedac.ciesin.columbia.edu

EO Toolkit	Earth Observations Toolkit for Sustainable Cities and Human Settlements	https://eotoolkit.unhabitat.org

Commercial satellite data and derived products are available through established Earth observation companies and their authorized distributors. Key commercial providers offering relevant high-resolution imagery and urban monitoring capabilities include Maxar, Planet, and Airbus Defense & Space, though this list is not exhaustive.

Data access and analysis is facilitated through cloud computing platforms:

- Amazon Web Services (AWS) Open Data Registry (http://registry.opendata.aws)
- Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog)

These platforms enable direct analysis without downloading large datasets locally, providing both open and commercial datasets through various licensing arrangements, along with computing resources and analysis tools. This cloud-based approach, when aligned with CEOS-ARD principles, helps address the growing challenges of data volume, reduce user effort in data processing, enabling direct analysis.

For commercial data access, users should consult with providers regarding current offerings, pricing, and licensing terms suitable for their specific needs.

d) Current EO Gaps (limitations)

Earth Observation (EO) is recognized as central to measuring this indicator, with more than 80% reliance on EO resources for its computation. However, several critical components of SDG 11.3.1 cannot be directly measured from space:

- Actual population counts and demographics, which must come from census or survey data
- Building occupancy rates and household sizes
- Distinction between residential and non-residential buildings without ancillary data
- Accurate measurement of building heights and urban densification in many contexts
- Temporal dynamics of population movement

EO has direct relevance for mapping and monitoring changes in built-up areas, and can support implementation of the DEGURBA harmonized approach recommended for its computation. EO can also help generate disaggregated maps of global, regional or national census data. An overview of EO opportunities, limitations and areas for improvement, relating to indicator 11.3.1, is presented below under two thematic areas: surface characterization and population.

Surface Characterization (Land Consumption Rate)

EO data is well equipped for mapping built-up area. As of today, several global datasets are available, such as the Global Human Settlement Built-up (GHS BUILT) developed by JRC/EC, the Global Urban Footprint (GUF) and the World Settlement Footprint developed by DLR, and the GMIS and HBASE data sets developed by NASA/University of Maryland, among others. Other relevant datasets are listed in the tables below.

The World Settlement Footprint 2015 (WSF 2015), developed by DLR/ESA provides a global overview of the world's human settlements in 10-meter resolution. The most recent WSF 2019 features data from the Sentinel-1 and Sentinel-2 missions, while the WSF Evolution is generated by processing seven million images from the Landsat satellites collected between 1985 and 2015 to provide detailed information about the spatiotemporal development for each human settlement identified in the WSF 2015, over the last 30 years. The WSF 3D provides a detailed quantification of the average height, total volume, total area and the fraction of buildings at 90 m resolution worldwide. Additional WSF datasets expected to be released in 2025 are WSF2019 imperviousness (10m resolution layer where each pixel marked as settlement is associated with the estimated percent impervious surface), WSF population (a 10m resolution layer derived by combining the WSF3D height information, WSF2019 imperviousness, and CIESIN population statistics where each pixel marked as settlement is associated with the estimated number of inhabitants), and WSF tracker (10m resolution layer providing bi-annual settlement extent updates from 2016 to 2024).

The 2023 release of GHS BUILT combines state-of-the-art Sentinel-2 and Landsat observations to improve the classification of built-up surface fraction (sub-pixel) and volume for the period 1975-2020. and Copernicus GHSL will ensure updates for 2022-24-26.

Although impressive in terms of high spatial resolution and global coverage, these data sets come with certain caveats. For example, the GUF relies solely on radar imagery and the public can only access an aggregated version of the GUF product (i.e. 75 meters vs. the full resolution in 12 meters) and only for the year 2012.

Other relevant global data sets include the Global Man-made Impervious Surface (GMIS); the companion Global Human Built-up and Settlement Extent (HBASE), developed by NASA/University of Maryland. These data sets are at 30-m spatial resolution and provide sub-pixel estimates of percent (%) man-made imperviousness at the global scale from Landsat. They do not, however, contain multiple epochs. Because the base data used for GMIS are from the Global Land Survey 2010 (GLS) Landsat archive for the epoch 2009-2011, there are still areas with perennial cloud cover (e.g. Indonesia) where there is “no data” over some urban centers. The GMIS and HBASE data is available for open public access through NASA's Socioeconomic Data Applications Center (SEDAC), hosted by Columbia University.

The GMIS data set is used as a fundamental component to produce reference data for the Trends.Earth Urban Mapper effort, developed by Conservation International (CI) in collaboration with NASA/GSFC researchers. The Trends.Earth Urban Mapper is an alternative solution for mapping built-up areas using the GMIS data set and archived Landsat imagery (i.e. from 2000 to 2015) within Google Earth Engine. Another dataset, currently in production by Boston University, will include global land cover time series at 30-m spatial resolution with a “developed” class. This dataset will provide a timely, consistent, and accurate calculation of the land consumption rate across the globe. The dataset covers the period 2001-2019 as an annual time series.

While global data sets provide a useful resource for monitoring the 11.3.1 indicator, they also have limitations in their application to track city level trends or with respect to definitions, available reference years and spatial resolution. For example, the definition of built-up area in the indicator metadata specifies ‘all areas adopted by buildings’. Although the GHS-BUILT, GUF and WSF, define built-up area in these terms, the GMIS includes all types of man-made impervious surfaces, and is only available for a single year, 2010.

And while Trends.Earth Urban Mapper is better aligned in terms of the built-up area definition, the approach is currently limited to Landsat imagery, having a coarser spatial resolution as compared to Sentinel-2 imagery. Sentinel data, however, are only available from 2015-2017 onwards, while the Landsat archive dates back to 1975. New efforts to produce a Harmonized Landsat Sentinel (HLS) data set show much promise to provide future Landsat-scale data at much improved temporal resolution.

Some of the aforementioned issues can be addressed by countries' investing their own resources in mapping built-up areas. For example, Mexico is already developing Geospatial Data Cubes to enable processing and analysis of satellite images for mapping built-up areas as well as other critical land surface indicators. In Colombia, the National Administrative Department of Statistics, used open catalogs of satellite images such as Landsat and Sentinel-2 to determine urban land consumption, using cloud-based tools such as Google Earth Engine.

The National Land Cover Dataset (NLCD) produced by USGS for the U.S. territory, based on Landsat data, is another example of this type of effort. Such activities may not, however, be feasible for countries without the same level of resources and infrastructure to produce similar, consistent data sets.

Recommendations: Today, the most realistic and feasible option for national built-up area mapping is to use the freely available datasets provided by the ESA Sentinel-1 (SAR) and Sentinel-2 (multispectral) as well as the USGS/ NASA Landsat (multispectral) and the NASA/NOAA Suomi NPP missions. These open datasets provide systematic multi-sensor acquisitions with a large potential for advancing the mapping of built-up areas. Open source tools such as SNAP, QGIS, Massive Spatial Automatic Data Analytics (MASADA), Google Earth Engine, and Microsoft Planetary Computer can support the mapping of built-up areas from Earth Observations. Users should be aware that significant computing and data storage resources are required when working at the national scale with annual or longer time series of Landsat, Sentinel-1 and Sentinel-2 data. Links to existing and well-established data infrastructures or cloud platforms with co-located satellite datasets (e.g. Google Earth Engine, DIAS etc.) can be helpful, in this regard. Countries who want to pursue their own mapping are advised to assess and identify their requirements for assistance from a national entity/GIS unit or assistance from a specialized service provider.

It is also worth mentioning that commercial satellite imagery with meter and submeter spatial resolution offers an opportunity to map the built-up area in higher detail compared to the free and open datasets. For national scale mapping, the use of commercial high-resolution imagery can be prohibitively costly for many countries but may be considered in a multi-scale approach, where the national built-up inventory is based on public domain data or from open datasets that are complemented with detailed built-up inventories for selected cities based commercial high- resolution imagery. The NASA Commercial Satellite Data Acquisition Program may partially alleviate this cost issue. However, thus far, there are no consistently processed commercial satellite data sets that could be used for regional or continental urban change mapping. Effective tools and processing algorithms are still needed to produce consistent atmospherically corrected, mosaiced data sets for large regions covering entire large urban areas.

Furthermore, we note a need for further advancing three-dimensional methods to capture building volume changes, tracking, thus, vertical growth of urban environments. This is possible through C-band SAR radar data (e.g., Sentinel-1) that can improve the accuracy of the 11.3.1 indicator. Lastly, regardless of the input satellite imagery, users should be aware of the fact that the direct output of EO processing is a map of the built-up area, and post-processing is needed to derive urban boundaries and the degree of land consumption to compute this indicator.

Recent public data products developed using very high-resolution satellite information could be used as a good starting point for settlement mapping that can be updated using change detected in open imagery. Microsoft and Google building footprints are available for many countries. The HRSL maps population based on settlement detection from high-resolution commercial imagery, while the GRID3 settlement layer also uses Commercial high-resolution inputs to develop extents for Africa. While none of these datasets has a time series component, they can be used as a base to measure change going forward. In addition, these high-resolution building footprints can be used as training labels for deep learning models to produce future high quality builtup maps using open EO data such as Sentinel-1 and Sentinel-2, as demonstrated by Hafner et al. (2022).

Population (Population Growth Rate)

Although in the first instance population statistics should be obtained through national statistics offices, there may also be a role or EO in determining the distribution of population. Indeed though, there are established methodologies for estimating population and densities from space-based data. For example, population datasets can be generated by obtaining sub-national population statistics (e.g. districts, counties, provinces) and subsequently distributing them geographically using geospatial covariate datasets such as the location of urban centres (cf. urban extent), landcover types, the main transportation network, i.e. roads, railroads and rivers etc. Even where these methodologies produce uncertainty, this uncertainty can be quantified to arrive at defensible estimates of population. By knowing the type and use of the urban fabric, coarse resolution population maps can be disaggregated to obtain a more accurate spatial assignment of the population density.

Global population data sets include the GHS-POP by JRC/EC, Gridded Population of the World (GPW) v4 by CIESIN/Columbia University, and the WorldPop global datasets by WorldPop, among others. These data sets provide information about human population distribution density. Users should be mindful of the reference year, and that population information derived from the census may be outdated. These datasets are all available for multiple time periods based on census inputs, however, not all countries have inputs from multiple census years, so the change in population is calculated based on national data in a number of cases. Even where multiple censuses were used to estimate population growth sub-nationally, the level of detail in the administrative unit data in many cases does not differentiate population change in enough spatial detail to be measured for individual urban areas.

Modeled population surfaces use urban growth as measured by land cover classifications, nighttime lights, and other sources as input predictors for disaggregating census population to pixels and urban areas. Using these predicted population surfaces to estimate population change at the urban level for comparison to urban extent change is problematic, given the interplay between urban change and population distribution in the models. Household survey data on population at the urban area level may be used to measure/estimate changes in population characteristics/demographics, and in turn to better estimate trends and dynamics in populations within urban extents.

The POPGRID Data Collaborative, funded by NASA and the Bill and Melinda Gates Foundation, aims to advance the use and impact of geospatial population and infrastructure data. POPGRID strives to bring together and expand the international community of data providers, users, and stakeholders from both the public and private sectors to accelerate the development and use of high quality, georeferenced data on population, human settlements, and infrastructure. The POPGRID Mapping Tool serves as a functional platform for data users across sectors to compare data, share tools, and report progress on data accessibility, quality, metadata, interoperability, intercomparison, validation, and use.

POPGRID also provides a summary of gridded population data set characteristics. Other tools produced by GHSL and WorldPop allow users to produce population grids for the area of interest.

e) Future Satellite EO Missions of Relevance

- NISAR (2025): NASA-ISRO SAR Mission will provide information about biomass, natural hazards, sea level rise, and groundwater, with urban areas as an intended parameter within ecosystems and agricultural monitoring.
- Landsat Next (2031): New observatory generation with advanced temporal, spatial, and spectral resolution of Earth surface observation supporting rapid analysis and decision-making for environmental change management.

f) EO-based global products

Product name	Satellite data used	Method	Comment
Built-up datasets			
The Global Human Settlement Built-up (GHS BUILT)	Landsat; Sentinel	Automatically retrieve information about built-up surface and volume extent at 5 years interval between 1975, and 2020	Developed and maintained by the European Commission's Joint Research Centre (JRC).
The Global Urban Footprint (GUF)	TerraSAR-X and TanDEM—X	Based on 2010–2014 X-band SAR (Synthetic Aperture Radar) imagery. It shows urban, non-urban and water areas globally at resolutions up to 12 m (75 meters for public access).	Developed by the German Aerospace Center (DLR)

Product name	Satellite data used	Method	Comment
The World Settlement Footprint (WSF): WSF 2015, WSF 2019, WSF evolution, WSF 3D	Sentinel-1, Sentinel-2; Landsat (WSF evolution) TerraSAR-X and TanDEM-X (WSF3D)	Uses mass collections of Landsat and Sentinel-1 imagery from 2014-15 timeframe, to provide a global overview of the world's human settlements. The World Settlement Footprint Evolution (WSF Evolution) generated by processing seven million images from the US Landsat satellite collected between 1985 and 2015 is also available. The WSF3D offers first three-dimensional survey of global building stock (90m spatial resolution; building area, fraction, height and volume.	WSF has been developed by DLR, partially under ESA funds.
Atlas of Urban Expansion		An open-source online resource with maps, satellite images, and data on spatial changes in cities around the world from 1990 to 2015.	The atlas is created in partnership by the Lincoln Institute of Land Policy, UN-Habitat, and New York University
High Resolution Settlement Layer (built-up area)	High-resolution settlement extent datasets	Uses computer vision techniques to classify blocks of optical satellite data as settled (containing buildings) or not. The settlement layer has been developed for 33 countries.	Developed by the Connectivity Lab at Facebook
The Global Man-made Impervious Surface (GMIS) Dataset From Landsat (NASA SEDAC)	Landsat; Global Land Survey (GLS) data for the 2010 target epoch	Generated from a massive reference training set produced from unclassified commercial satellite data using machine learning algorithms.	A 30m spatial resolution dataset that provides sub-pixel estimates of % imperviousness and Associated standard error fields. Data processed to surface reflectance.
The Human Built-up And Settlement Extent (HBASE) Dataset	Landsat; Global Land Survey (GLS) data for the 2010 target epoch	Generated from a massive reference training set produced from unclassified commercial	The dataset represents the maximal extent of man-made impervious cover across the world and is a

Product name	Satellite data used	Method	Comment
from Landsat (NASA SEDAC)		satellite data using machine learning algorithms.	binary classification (HBASE/non-HBASE) with associated probability estimates of class membership. A companion global dataset to the GMIS dataset, at 30m spatial resolution.
Microsoft Building Footprints	High-resolution commercial satellite imagery (optical)	Developed using machine learning	A near-global collection of footprints.
Google Open Buildings / Open Buildings 2.5D Temporal	High-resolution satellite imagery (optical)	Open, buildings footprint dataset developed using machine learning. A spatio-temporal dataset of building footprints and heights derived from Sentinel-2 imagery.	Open building footprint data available for Africa, Latin American, and large parts of Asia. Building presence, counts and heights at 4-meter resolution across Africa, South Asia, South-East Asia, Latin America and the Caribbean (2016-2023)
Overture Map Data	Building data integrated from multiple sources		Consortium of organizations have formed the Overture Maps Foundation to release it.
Sub-Saharan Africa Settlement Extents		Settlement extents calculated based on building densities (buildings extracted from high-resolution commercial imagery).	
GLanCE			Time series of land cover (including developed) at 30m resolution.
WorldPop settlement and building datasets			Gridded 100m datasets on a range building pattern metrics, residential classifications and density measures for all countries in sub-Saharan Africa.
Population Datasets			
Global Human Settlement population (GHS-POP)		Uses GHS-BUILT layer to make a spatial prediction of population census data	

Product name	Satellite data used	Method	Comment
WorldPop (Data Catalogue)		Produced as gridded, time-series products derived from census and household survey data.	Open access archive of Global spatial demographic and population mobility Datasets. Additionally, bespoke national population and settlement datasets constructed in collaboration with national statistical offices using census disaggregation (top-down) or prediction (bottom-up) models.
Gridded Population of the World (GPW)		Models the distribution of human population (counts and densities) on a continuous global raster surface (~1 km resolution).	GPW is developed and maintained by CIESIN.
High Resolution Settlement Layer (population estimate)		Uses estimates of human population distribution (number of persons and extent of settlements) at a resolution of 1 arc-second (approximately 30m) for the year 2015.	The population estimates are based on recent census data and the high-resolution settlement extent developed by the Connectivity Lab at Facebook (cf. High Resolution Settlement Layer (built-up area)). CIESIN used proportional allocation to distribute population data from subnational census data to the settlement extents. The population data have been developed for 33 countries.

The Metadata also makes reference to UN DESA population data. It is important to mention the fact that census data should be readily available from national statistical offices (NSOs), although the level of disaggregation may vary from country to country. In this regard, EO can provide support for disaggregating population data.

g) Platforms and Tools

There are several online platforms and tools that provide options and support for accessing or deriving various inputs for computation of indicator 11.3.1.

- **Degree of Urbanisation Toolkit GHS-DEGURBA Toolkit (v2.1)** is a single installation package for the GHSL tools needed for the implementation of the Degree of Urbanisation.

Alternatively, the application of the Degree of Urbanisation to the GHSL data is available globally in 5 year intervals for download here. When selecting the reference year 2020 also the corresponding vector outlines are provided.

● **The Earth Observations Toolkit for Sustainable Cities and Human Settlements**: On February 25, 2021, the Earth Observations for Sustainable Development Goals (EO4SDG) initiative and UN Habitat launched the Earth Observations Toolkit for Sustainable Cities and Human Settlements at the 52nd session of the UN Statistical Commission. The Toolkit is a collaborative effort that improves countries' and cities' capacity on, and makes more accessible, Earth science resources related to SDG 11 indicators. It involves contributions from over 40 organizations, and contains resources, such as data, tools, use cases and learning opportunities, that are related to four primary thematic areas: adequate housing, open spaces, access to public transport and spatial urbanization. It is part of the global urban monitoring framework that UN Habitat designed for monitoring SDGs and other city objectives such as inclusiveness, resilience and safety. Read also UN Habitat's report to the UN Statistical Commission during its 53rd session in March 2022.

● **Global Human Settlement Layer** **(GHSL)** is a framework that provides new spatial data mining technologies for the automatic processing, analytics and knowledge extraction from large amounts of heterogeneous spatial data. Amongst others these tools provide users with options to map built-up areas from remote sensing data as well as estimating the land use efficiency from the GHSL and in support of measuring SDG 11.3.1.

● **Trends.Earth** is an online platform from Conservation International (CI) and NASA for monitoring land change using earth observations in an innovative desktop and cloud- based system. Amongst others, Trends.Earth Urban Mapper allows users to produce built-up area maps at selected time steps using a combination of the full Landsat archive between 1997 and 2019, and the GMIS dataset (Brown de Colstoun et al 2017). Trends.Earth computes a series of impervious surface indices globally available at 30m resolution to inform on urban extent for the years 2000, 2005, 2010, and 2015. Combined with user input and population data, the tool computes SDG 11.3.1 both in the form of maps and tables for ease of interpretation and reporting.

● The **Urban Thematic Exploitation Platform** (U-TEP) presents a web-based platform that allows users to effectively utilize Earth Observation (EO) imagery and existing auxiliary data (e.g., geo-data, statistics) to measure and assess key properties of the urban environment and monitor the past and future spatiotemporal development of settlements. In particular it is worth mentioning that U-TEP offers dedicated tool for SDG11.3.1 monitoring and reporting based on the WSF global datasets:

● **WorldPop** provide a wide range of GIS plugins for accessing and processing spatial demographic datasets, applications for constructing and interacting with spatial population data, and an API for accessing data. These are all summarised, together with training materials, tutorials and examples in GEO's knowledge hub for top-down population modelling and bottom-up estimation modelling.

● The **POPGRID** Data Collaborative aims to bring together and expand the international community of data providers, users, and sponsors concerned with georeferenced data on population, human settlements and infrastructure. Such data can help improve access to public and private services, increase the sustainability of natural resources, and facilitate progress towards meeting the internationally accepted SDGs

h) International Initiatives

GEO Human Planet Initiative (HPI) is committed to developing a new generation of measurements and information products that provide novel evidence-based assessment of the human presence on the planet Earth. The Human Planet leverages advances in Earth Observation technologies and geo-spatial data analytics for improving the global awareness on the spatial patterns and processes of today's urbanizing world. The GHI core partners include Joint Research Center (JRC), Global Human Settlement Layer project (GHSL), the University of Southampton WorldPop project, and the Columbia University, Center for International Earth Science Information Network (CIESIN) but all together more than 150 individual scientists and policy makers belonging to 85 different organizations are involved.

GEO Global Urban Observation and Information (GUOI) intends to improve urban monitoring and assessment through international cooperation and collaboration, to provide datasets, information, technologies to pertinent urban users (World Bank, UN, and planning and environmental management agencies, especially in developing countries), and to support UN SDG Goal 11: Make cities inclusive, safe, resilient and sustainable. This Initiative will generate various data products of global urban areas using Earth Observation (EO) data, provide EO-

based urban data services through various systems and tools, develop new models and algorithms to detect, assess, monitor, and model urban areas and environments, create new knowledge to fill the gaps in the integration of EO and other datasets for a better understanding of cities and develop essential urban variables and indicators for sustainable cities

Earth Observations for Sustainable Development Goals (EO4SDG) is an international initiative from the Group on Earth Observations that organizes the potential of EO to advance the *2030 Agenda* and enable societal benefits through achievement of the Sustainable Development Goals. The initiative's goals include demonstrating practical EO data uses, building capacity, promoting data access, and supporting country and stakeholder adoption of EO for SDG implementation, monitoring, and reporting. In 2020, EO4SDG collaborated with UN Habitat, the GEO Human Planet and GUOI initiatives, and over 40 organizations across regions to develop the *Earth Observations Toolkit for Sustainable Cities and Human Settlements*. The Toolkit is a collaborative effort that improves countries' and cities' capacity on, and makes more accessible, Earth science resources related to SDG 11 indicators and the New Urban Agenda.

3. EO-BASED MONITORING METHODOLOGY

Timeframes (Indicator VS EO considerations):

- Indicator: according to the latest metadata, it is anticipated that countries can report consistently in 5-10 year intervals, allowing for three to four reporting points until the year 2030.
- EO timeframe considerations: Technology is mature and EO services already established and in use.

Step-by-Step guide for EO integration into SDG indicator framework

The Metadata on SDG Indicator 11.3.1 (version: March 2021) outlines in detail the current method of computation including a section on data sources and collection. The latter explicitly mentions satellite data as a key information source to be incorporated into the reporting framework. The metadata is further expanded in a step by step guide by UN-Habitat, which explains the approach of extracting relevant data from EO in the Google Earth Engine Platform, and documents some of the current global datasets relevant for the indicator.

Some key questions that countries can consider before integrating EO into the 11.3.1 indicator reporting are the following: Do the freely available products meet requirements in terms of spatial resolution, frequency, continuity, period of interest and accuracy? Is in-house capability available and adequate? Is training needed? Are local and international resources required? The relevance of these questions is exemplified below in the outline of the basic steps that need to be followed by users who wish to integrate EO for estimation of indicator 11.3.1.

STEP 1: Get data

As a first step, users need to assess their existing national datasets, capacities to produce city-level data from existing EO resources, then check the available public domain datasets for representativeness of the reporting period a. If the public domain EO products and datasets are considered inadequate users have the option to acquire new EO imagery and census data to generate updated information on urban extent and population distribution. Typically, census data will be obtained through the NSO while users who wish to acquire new EO imagery to generate updated information on urban extent can choose between openly available imagery (e.g, Landsat and Sentinel) and commercial high-resolution imagery – or a combination of both.

Users can leverage the Earth Observations Toolkit for Sustainable Cities and Human Settlements resources (e.g., data products, tools, training resources) and step by step guides provided by the custodian agency to easily find and access data of interest to compute indicator 11.3.1.

STEP 2: Process data

Although built-up and/or impervious surface mapping is an established field within Earth Observation applications, classification approaches tend to vary according to the sensors used and the objectives and scale of each study. In most cases, however, the acquired input data is subject to standard pre-processing routines for orthorectification, atmospheric correction and, if relevant, topographic normalization. The mapping itself is typically done using either pixel or object-based image classification based on multi-sensor EO data (e.g. Sentinel-1 and -2) and using spectral, textural and/or contextual features to classify the extent of the built-up and non-built up impervious areas. It is recommended that outputs are subject to manual post-processing for refinement and quality control.

The thematic accuracy can be expected to be around 90% but deviation can occur depending on the character of the urban landscape. For this indicator, it is recommended to consider analysis periods with intervals of 5 or more years. Based on pilots undertaken by UN-Habitat, shorter time intervals do not produce significantly different results, unless such analysis is undertaken using high resolution (and often costly) satellite imagery. It is recommended, but not required, to explore the Landsat archive for historic analysis to better understand urban growth trends and how these affect sustainable development.

Once the area of interest has been defined (preferably based on the recommended harmonized DEGURBA methodology), users need to estimate how many people live within those areas. The best source of the population data is the national statistical office in each country. In the absence of high-resolution population data from the NSO, users can rely on gridded population data referred to above.

A summary of key characteristics of gridded population data sets provided by the POPGRID Data Collaborative can also be accessed.

STEP 3: Validate the results

Validation is defined as the process of establishing evidence to provide a high degree of assurance that a specific process will consistently generate a product meeting its predetermined specification and quality attributes. Validation is important for any application of Earth Observation as it establishes the expected accuracy and uncertainties of a derived product and hence its credibility for an intended usage. Validation should adhere to a set of fundamental requirements, including: **independence**, i.e. only using data and experts which have not been part of the data set production; **timeliness**, i.e. only using reference data which are timely and frequent enough to evaluate the accuracy of a given product; and **validity**, i.e. always using reference data with a higher quality than those used for the data set production.

As the number of pixels and/or objects in EO maps is too large to be surveyed in its entirety, the most popular data validation methods rely on sampling. The sampling needs to be carefully designed to ensure statistical validity, yet still accommodating practical realities in terms of cost and time constraints. Various probability sampling designs are suitable to assess the accuracy of maps. The most commonly used are based on simple random, stratified random, and systematic selection of sampling units. No single sampling design can serve as a universally appropriate design; however, stratified random sampling is a practical and cost-efficient design that satisfies the basic accuracy assessment objectives and most of the desirable design criteria. Stratified random sampling affords the option to increase the sample size in classes and/or regions that occupy a small proportion of area to reduce the standard errors of the class/region-specific accuracy estimates for these rare occurrences. A further advantage of stratified random sampling is also the ability to augment a sample when new data or updates become available without compromising the statistical rigor.

Independent, timely and valid sample data is typically gathered from field observations and/or from higher resolution imagery acquired by satellite, flight or drone-borne sensors. In all cases the urban vs. non-urban margin can easily be interpreted and it is the general expectation that the validation of built-up areas and the derived urban extent maps against such reference data should return a classification accuracy of 90%.

4. RECOMMENDATIONS FOR IMPLEMENTATION

a) Activities

- Leverage the Earth Observations Toolkit for Sustainable Cities and Human Settlements resources (e.g., data products, tools, use cases, training resources) to easily find and access available data and EO-processing tools of interest to compute indicator 11.3.1.
- Evaluate the usefulness of global public domain datasets and tools for national reporting. This could be done for a few selected countries where SDG 11.3.1 has already been estimated with good quality, high resolution input layers that can act as a reference.
- Implement a few country studies where SDG 11.3.1 is estimated by taking full advantage of the Landsat and Sentinel imagery for temporal mapping of built-up and non-built-up impervious areas and estimation of urban extent. Leverage national census data to assess the population growth rate, and combine the two to calculate 11.3.1.
- Run processing tests and prepare a design document that details the computing and data storage requirements for countries who wish to take advantage of time-series of Landsat, Sentinel-1 and Sentinel-2 data for SDG 11.3.1 estimation and reporting. The design document could also detail how similar resources could be requested through well-established data infrastructures or cloud platforms.

b) Timeframes

Indicator timeframe considerations: According to the latest metadata, It is anticipated that countries can report consistently in 5-10 year intervals, allowing for three to four reporting points until the year 2030.

EO timeframe considerations: Technology is mature and EO services are already established and in use.

c) Use Cases

- Japan documentation on EO/statistical data computation (ArcGIS Storymap in the works)
  - Indicator metadata
  - Validation methodology
- EO4SDG
  - Sweden use case, 2019
  - Canada use case, 2016
  - Portugal use case, 2019
- EO Toolkit
  - Using Earth Observation Data to Calculate Sustainable Urbanization in Colombia
  - Using Earth Observations to Calculate SDG Indicator 11.3.1, Ratio of Land Consumption Rate to Population Growth Rate in UAE
  - SDG 11 Indicators Reporting in Poland: The Role of Earth Observations and Dasymetric Maps
    - Supporting document
  - SDG Indicator 11.3.1 Reporting in South Africa
    - Supporting document
  - Alexander von Humboldt Institute's Use of Earth Observations to Monitor SDG 11 in Colombia
    - Supporting document
  - China's Platform on Global Observation of Urban Land-Cover Composite and Thermal Environment for Improving Urban Sustainability

- Supporting document

5. TRAININGS

- ARSET-Remote Sensing For Monitoring Land Degradation and Sustainable Cities (SDG)
  - ARSET-Introduction to Population Grids and their Integration with Remote Sensing Data for Sustainable Development and Disaster Management
- ARSET - Earth Observations Toolkit for Sustainable Cities and Human Settlements
- Statistical population modelling for census support: https://wpgp.github.io/bottom-up-tutorial/
- Small area population estimates using random forest top-down disaggregation: https://data.worldpop.org/repo/docs/lazar2021poprf, https://data.worldpop.org/repo/docs/leasure2021small/
- Degree of Urbanisation training course: https://academy.europa.eu/courses/the-degree-of-urbanisation

6. REFERENCES

About the SDG Indicator

- Indicator 11.3.1 Metadata (March 2021): https://unstats.un.org/sdgs/metadata/files/Metadata-11-03-01.pdf

Publications & policy papers

- Ramírez Gutiérrez, M. Ángel, Lasso Rodríguez, J. C. y Durán Gil, C. A. (2023). Integración de información estadística y observaciones de la Tierra para el cálculo de indicadores ODS 11.3.1 y 11.7.1 en Colombia, aplicando técnicas de clasificación Random Forest. Cuadernos de Geografía: Revista Colombiana de Geografía, 32(1), 226–257. https://doi.org/10.15446/rcdg.v32n1.98039
- Schiavina, M., Melchiorri, M., Freire, S., Florio, P., Ehrlich, D., Tommasi, P., ... & Kemper, T. (2022). Land use efficiency of functional urban areas: Global pattern and evolution of development trajectories. Habitat International, 123, 102543. https://www.sciencedirect.com/science/article/pii/S0197397522000406
- Melchiorri, M., Pesaresi, M., Florczyk, A. J., Corbane, C., & Kemper, T. (2019). Principles and applications of the global human settlement layer as baseline for the land use efficiency indicator—SDG 11.3. 1. ISPRS International Journal of Geo- Information, 8(2), 96. https://www.mdpi.com/2220-9964/8/2/96
- Schiavina, M., Melchiorri, M., Corbane, C., Florczyk, A. J., Freire, S., Pesaresi, M., & Kemper, T. (2019). Multi-scale estimation of land use efficiency (SDG 11.3. 1) across 25 years using global open and free data. Sustainability, 11(20), 5674. https://www.mdpi.com/2071-1050/11/20/5674
- Corbane, C., Politis, P., Siragusa, A., Kemper, T. and Pesaresi, M., LUE User Guide: A tool to calculate the Land Use Efficiency and the SDG 11.3 indicator with the Global Human Settlement Layer, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-73631-5 (print); 978-92-79- 73630-8 (pdf), doi:10.2760/16919 (print), 10.2760/212689 (pdf), JRC108026
- Esch, T., Bachofer, F., Heldens, W., Hirner, A., Marconcini, M., Palacios-Lopez, D., ... & Gorelick, N. (2018). Where we live—A summary of the achievements and planned evolution of the global urban footprint. Remote Sensing, 10(6), 895.
- Gallery, M., & Sensing, R. Gridded Population of the World (GPW) v4.
- Pesaresi et al. 2016. Atlas of the Human Planet - Mapping Human Presence on Earth with the Global Human Settlement Layer https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/atlas-human-planet-mapping-human-presence-earth-global-human-settlement-layer
- Leyk, S., Gaughan, A. E., Adamo, S. B., de Sherbinin, A., Balk, D., Freire, S., Rose, A., Stevens, F. R., Blankespoor, B., Frye, C., Comenetz, J., Sorichetta, A., MacManus, K., Pistolesi, L., Levy, M., Tatem, A. J., and Pesaresi, M.: The spatial allocation of population: a review of large-scale gridded population data products and their fitness for use, Earth Syst. Sci. Data, 11, 1385–1409, https://doi.org/10.5194/essd-11-1385-2019, 2019.
- Leasure, D. R., Jochem, W. C., Weber, E. M., Seaman, V., & Tatem, A. J. (2020). National population mapping from sparse survey data: A hierarchical Bayesian modeling framework to account for uncertainty. Proceedings of the National Academy of Sciences, 117(39), 24173-24179.
- Boo, G., Darin, E., Leasure, D. R., Dooley, C. A., Chamberlain, H. R., Lázár, A. N., Tschirhart, K., Sinai, C., Hoff, N. A., & Fuller, T. (2022). High-resolution population estimation using household survey data and building footprints. Nature communications, 13(1), 1330.
- Wardrop, N., Jochem, W., Bird, T., Chamberlain, H., Clarke, D., Kerr, D., Bengtsson, L., Juran, S., Seaman, V., & Tatem, A. (2018). Spatially disaggregated population estimates in the absence of national population and housing census data. Proceedings of the National Academy of Sciences, 115(14), 3529-3537.
- McKeen, T., Bondarenko, M., Kerr, D. et al. High-resolution gridded population datasets for Latin America and the Caribbean using official statistics. Sci Data 10, 436 (2023). https://doi.org/10.1038/s41597-023-02305-w