Annual high-resolution global ambient population estimates from 1975 to 2024

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ABSTRACT

Gridded population data support assessments of human exposure, settlement change, infrastructure demand, and access to services, yet global datasets combining annual coverage over multiple decades with fine spatial resolution remain limited. LandScan Mosaic Time Series provides 50 annual estimates of global ambient population distribution at 3 arc-second resolution from 1975 through 2024. The series is anchored to the 2024 LandScan Mosaic surface, produced through a building-level population modeling workflow. Historical surfaces are reconstructed using annualized changes in built surface and derived first-level administrative population trajectories. Every layer, including 2024, is normalized to administrative targets scaled to annual country totals from the U.S. Census Bureau International Database. The dataset is distributed as 50 single-band Cloud Optimized GeoTIFFs on an identical WGS84 grid, with values representing estimated persons per cell. Its common grid and methodology support fine-scale longitudinal analysis of ambient population distribution while documented validation and limitations guide appropriate reuse.

Background & Summary

High-resolution gridded population datasets are widely used in studies of urbanization, infrastructure planning, resource allocation, disaster risk, environmental exposure, public health, and survey design[1–3]. Many applications require population estimates that are both spatially detailed and temporally consistent. Such data can reveal heterogeneous city-level demographic trajectories that are obscured by national and regional aggregates[4]. However, gridded population products are often optimized for a single reference year or produced through workflows that change across releases, which can limit their suitability for pixel-level change detection and long-term analysis[1,5].

LandScan has evolved through several generations of population modeling. A prototype of LandScan Global was developed in 1998 to estimate populations at risk from natural and anthropogenic hazards, and LandScan Global subsequently developed into an annually released, 30 arc-second product using country-specific, multivariable dasymetric models to represent ambient—or unwarned, 24-hour average—population[5]. LandScan USA extended this framework in the 2000s with separate 3 arc-second daytime and nighttime population surfaces that explicitly represented routine movements of workers and students[20], while LandScan HD later generalized building- and facility-informed high-resolution ambient population modeling across countries[21]. More recently, LandScan Mosaic introduced a globally scalable building-level framework that propagates uncertainty in building use, floor count, and occupancy into population estimates[15]. Together, these developments progressively improved spatial resolution, population representation, and uncertainty characterization, but the resulting products were designed primarily as optimized estimates for particular reference periods rather than as a methodologically harmonized longitudinal record. This distinction is especially important for the annual LandScan Global editions: because their ancillary inputs and modeling procedures evolved between releases, their documentation cautions against interpreting cell-level differences between editions as population change[5]. LSM-TS addresses this longstanding limitation by holding the fine-resolution baseline, grid, population concept, and processing framework constant across years while introducing annual variation through a common built-surface record and consistently normalized demographic controls.

Existing global gridded population products differ in population concept (residential or ambient population distribution), spatial resolution, temporal coverage, input geography, and allocation method, making dataset selection a fitness-for-use decision rather than a simple choice of spatial resolution[1,6]. Census-preserving products such as Gridded Population of the World version 4 (GPWv4) provide global population grids for selected census-era years using proportional allocation from administrative units, while Global Human Settlement Layer Population Grid (GHS-POP) provides built-up-informed residential population grids across historical and projected epochs[7,8]. WorldPop, High-Resolution Settlement Layer (HRSL), and related products use high-resolution geospatial covariates and dasymetric modeling approaches to redistribute population counts[9–12].

Recent annual products such as GlobPOP further demonstrate demand for temporally consistent gridded population surfaces for longitudinal analysis[13]. GlobPOP provides annual global population estimates for 1990–2020 at approximately 1 km resolution. Within this landscape, LSM-TS provides annual global ambient population estimates from 1975 through 2024 on a 3 arc-second grid. The spatial distribution and grid geometry are anchored to the 2024 LandScan Mosaic population surface[14,15]. Annual preliminary surfaces are generated by scaling the 2024 baseline according to changes in built-up surface from the Global Human Settlement Layer Built-Up Surface (GHSL-BUILT-S) product. Every annual surface, including 2024, is subsequently normalized to first-level administrative unit (ADM1) target populations. These targets represent the primary subnational administrative divisions within each country and are derived from LandScan Global subnational trajectories, then scaled within each country-year so that their sums equal annual U.S. Census Bureau International Database national population totals[16–18]. This design preserves a consistent fine-scale spatial modeling framework while introducing annual variation from a globally available built-environment time series and country-year-normalized subnational demographic controls.

LSM-TS represents ambient population, defined here as an average population distribution over a 24-hour period, rather than a strictly residential nighttime population[19]. This distinction is important for reuse because comparisons with census data and other gridded population datasets may reflect differences in population concept as well as differences in modeling approach. The dataset is intended for analyses that benefit from a consistent annual spatial framework, including historical exposure assessment, settlement expansion, accessibility modeling, retrospective infrastructure analysis, and other studies requiring long-term gridded population denominators.

This Data Descriptor describes the source data, processing workflow, released raster files, validation procedures, and practical limitations of the dataset. It does not present a scientific analysis of global population change; instead, it documents the construction and technical quality of the released data product. The present release should therefore be interpreted as the first version of a repeatable backcasting framework: it provides a fixed 1975–2024 dataset for reuse, while allowing future releases to incorporate newer LandScan Mosaic baselines and revised supporting data. Figure 1 provides example annual raster surfaces for selected urban regions across the time series.

Methods

Figure 2 summarizes the raster backcasting workflow. The workflow has five main stages: annual interpolation of GHSL-BUILT-S values, aggregation of the offset GHSL-BUILT-S grid to the LandScan Mosaic grid, derivation of annual built-surface scaling factors, adjustment of the 2024 ambient population baseline, and normalization to annual administrative population targets.

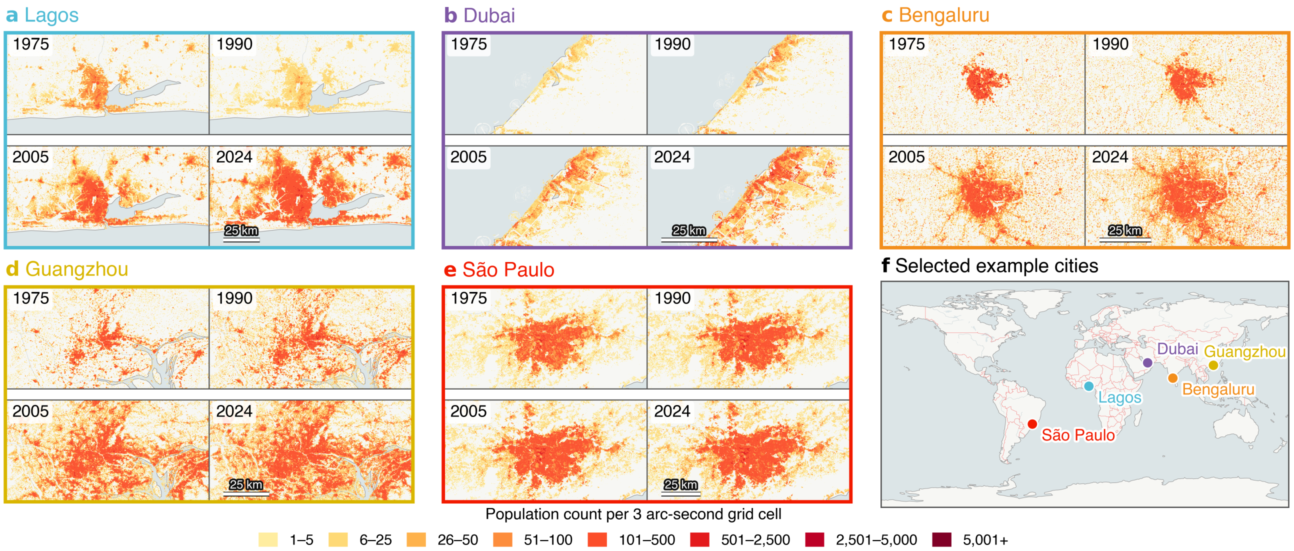

Figure 1. Example LSM-TS ambient population grids for selected urban regions. Panels show Lagos, Dubai, Bengaluru, Guangzhou, and São Paulo across selected years from 1975 to 2024, with a locator map showing the example city locations. Cell values represent estimated ambient population counts per 3 arc-second grid cell. The figure provides example spatial patterns from the released annual rasters and is intended to illustrate file content and interpretation rather than to present a formal analysis of urban change.

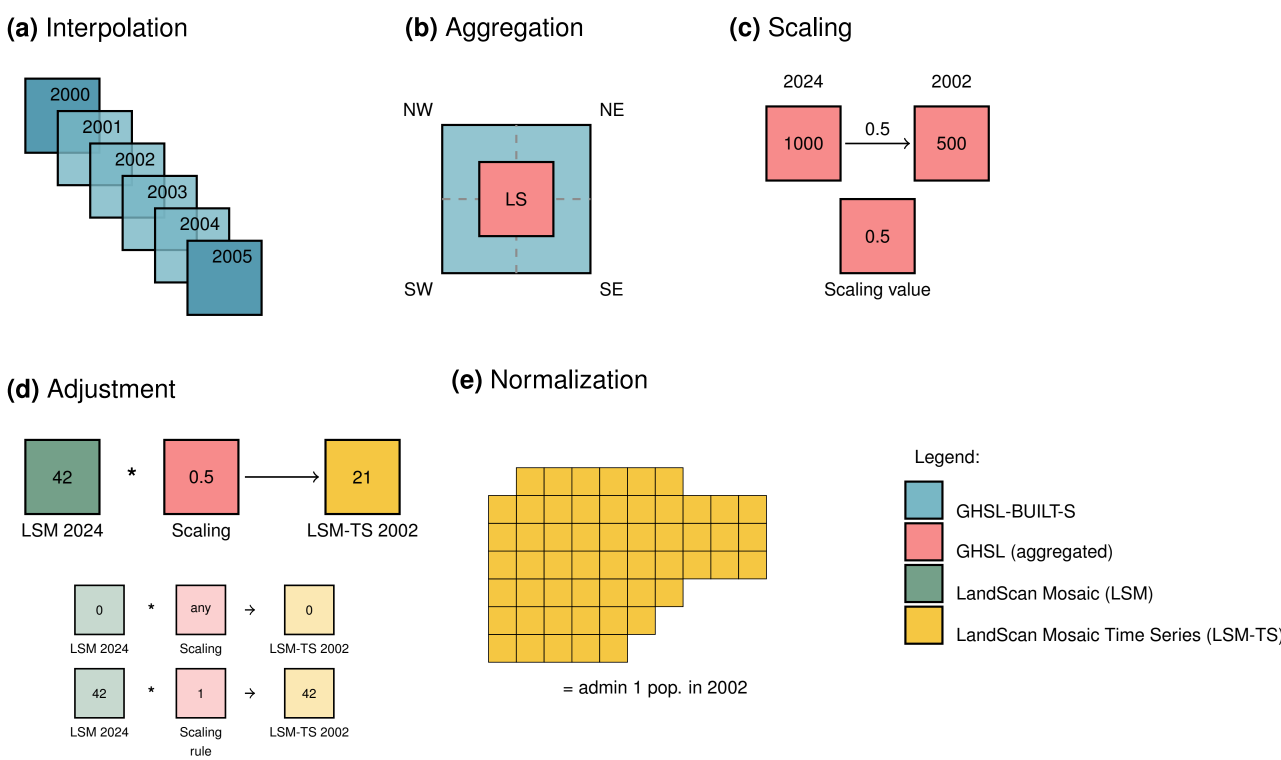

Figure 2. LSM-TS raster backcasting workflow. GHSL-BUILT-S values are interpolated to annual time steps, aggregated to the LandScan Mosaic grid, converted to scaling factors relative to the interpolated 2024 GHSL baseline, applied to the 2024 LandScan Mosaic ambient population benchmark, and normalized to annual ADM1 population targets. LSM denotes LandScan Mosaic, and LSM-TS denotes LandScan Mosaic Time Series. Zero-population and zero-denominator cases follow the rules described in Methods.

Input data

LSM-TS integrates five principal inputs: the 2024 LandScan Mosaic ambient population baseline, the Global Human Settlement Layer Built-Up Surface time series, authoritative annual national population totals, LandScan Global-derived subnational population trajectories used to construct ADM1 normalization targets, and a fixed administrative boundary geography used for target construction and validation. Table 1 summarizes these inputs.

Table 1. Primary input datasets used in the LSM-TS workflow.

Dataset	Spatial resolution	Temporal coverage	Role in workflow
LandScan Mosaic[14,15]	3 arc-second	2024	Baseline ambient population surface and target grid geometry.
Global Human Settlement Layer Built-Up Surface, R2023A[16,22]	3 arc-second	1975–2025 epochs; interpolated to annual values	Built-surface change proxy used to derive annual pixel-level scaling factors.
U.S. Census Bureau International Database[18]	National	1975–2024	Authoritative annual national population totals used to scale ADM1 trajectories within each country-year.
LandScan Global[5,17]	30 arc-second	2000–2024	Annual subnational population estimates aggregated to fixed country-ADM1 units and used to derive complete ADM1 target trajectories.
Administrative boundary geography[21,23]	Vector polygons	Fixed reference geography	LSIB-aligned country boundaries and harmonized ADM1 units used for target construction, raster-cell assignment, and administrative validation.

LandScan Mosaic baseline

The 2024 LandScan Mosaic ambient population surface provides the baseline population distribution and target grid geometry for all LSM-TS outputs. LandScan Mosaic is produced using a building-informed population modeling workflow and released on a global 3 arc-second grid[14,15]. In this release, only the ambient population layer is backcast and distributed. Daytime and nighttime population layers are not included in the present data release.

Built-surface time series

Historical built-surface change is represented using the Global Human Settlement Layer Built-Up Surface product (GHSL-BUILT-S), release R2023A[16,22]. The product provides built-up surface estimates at 5-year intervals. LSM-TS uses GHSL-BUILT-S epochs from 1975 through 2025 to derive annual built-surface values, including the interpolated 2024 baseline value needed to compute scaling factors relative to the LandScan Mosaic 2024 population surface.

Built-surface data are widely used in gridded population modeling because they provide spatially explicit information on settlement location and changes in population support[10,11,24,25]. In this workflow, GHSL-BUILT-S is used as a temporal proxy for changes in the built environment, not as a direct observation of population, occupancy, or residential use. This distinction is important because built area can support residential, commercial, industrial, institutional, or mixed uses, and because population density within built areas can change independently of built-surface extent.

Because 2024 is not a native GHSL R2023A reference epoch, the 2024 built-surface value used as the denominator for the scaling factors was linearly interpolated between the 2020 and 2025 GHSL epochs. Specifically, for each GHSL cell,

$$G_{i,j,2024} = G_{i,j,2020} + \frac{2024 - 2020}{2025 - 2020} \left(G_{i,j,2025} - G_{i,j,2020} \right).$$

The interpolated 2024 GHSL value is used as the denominator for the built-surface scaling factors. Consequently, the 2024 scaling factor equals one wherever the 2024 GHSL denominator is positive, so the preliminary 2024 surface retains the within-cell spatial values of the LandScan Mosaic baseline before administrative normalization. The released 2024 LSM-TS raster is then normalized through the same ADM1 control-total procedure applied to all other years.

Administrative boundary geography

A fixed administrative boundary geography is used to define country and ADM1 normalization units. Country boundaries follow the Large Scale International Boundaries (LSIB) representation used in the LandScan HD boundary workflow, while ADM1 boundaries are drawn from the harmonized subnational boundary sources described by Tuccillo et al.[21,23]. In that workflow, subnational boundaries are sourced from government agencies where available and supplemented by open boundary sources when needed, then harmonized and clipped to LSIB-aligned international boundaries.

The same fixed ADM1 geography is used for all years in LSM-TS. This design supports temporal consistency in target construction, raster-cell assignment, and administrative control-total validation. It also means that the workflow does not reconstruct historical administrative boundary changes; annual population targets are expressed on the fixed normalization geography used for this release.

Population control totals and ADM1 target trajectories

Annual national population totals are obtained from the U.S. Census Bureau International Database[18]. These values provide the authoritative country-year control totals used during normalization. Subnational ADM1 target trajectories are derived from LandScan Global annual population surfaces from 2000 through 2024[17]. LandScan Global-derived administrative population estimates were first aggregated to unique country-ADM1 units using the fixed ADM1 normalization geography described above. For each country-ADM1 unit, a linear trend was fit through the available annual population estimates and used to generate a complete annual ADM1 trajectory from 1975 through 2030. Although target trajectories were generated through 2030 for workflow continuity, the present release uses only the 1975–2024 targets. These targets are applied to all 50 annual rasters, including the 2024 baseline-derived layer.

Let $A_{a,t}$ denote the LandScan Global-derived population estimate for ADM1 unit a in observed year t, and let $\mathcal{O}_a$ denote the set of observed years available for that ADM1 unit. A linear trend was fit independently for each ADM1 unit:

$$\tilde{A}_{a,t} = \alpha_a + \beta_a t, \tag{1}$$

where α_a and β_a are the fitted intercept and slope. Fitted values were then bounded below to avoid negative or implausibly small extrapolated ADM1 populations. The lower bound for ADM1 unit a was defined as:

$$B_a = \max\left(500,\ 0.10 \times \min_{t \in \mathcal{O}_a} A_{a,t}\right), \tag{2}$$

and the bounded trajectory was calculated as:

$$A^*_{a,t} = \max\left(\tilde{A}_{a,t},\ B_a\right). \tag{3}$$

The lower bound prevents negative or near-zero extrapolated values, particularly for small administrative units or units with declining fitted trends. The constants in Eq. 2 were used as conservative safeguards rather than fitted model parameters: the absolute threshold of 500 persons prevents trajectories from collapsing to unrealistically small values, while the relative threshold of 10% of the minimum observed ADM1 population allows substantial decline but prevents projections far below the empirical population range. The bound is applied only to the intermediate ADM1 trajectory; final ADM1 targets are subsequently normalized within each country-year to match the authoritative national total.

Let $N_{c,t}$ denote the authoritative national population total for country c in year t, and let $a \in c$ indicate ADM1 units nested within country c. The final ADM1 target population used for normalization is:

$$T_{a,t} = A^*_{a,t} \cdot \frac{N_{c,t}}{\sum_{a \in c} A^*_{a,t}}. \tag{4}$$

This country-year scaling preserves the fitted subnational distribution within each country-year while ensuring exact agreement with the authoritative national control total. The approach supports consistent annual normalization across the full time series while holding the ADM1 normalization geography fixed through time. It does not reconstruct historical administrative boundaries or independently observe pre-2000 subnational population distribution.

Global grid alignment and preprocessing

All outputs are generated on the LandScan Mosaic 3 arc-second grid in geographic coordinates. The grid uses a global WGS84 coordinate reference system. Each grid cell is referenced using a consistent row and column indexing scheme, allowing annual rasters to be stacked and compared directly.

The LandScan Mosaic ambient raster is converted to a tabular representation containing row and column ID, administrative unit, and baseline ambient population value. Cells with positive baseline population are retained for pixel-level processing. Administrative labels are assigned using the fixed ADM1 normalization geography described above. Boundary rasterization is used for primary assignment, with nearest-feature assignment used to resolve populated cells that fall on boundary edges.

The GHSL-BUILT-S rasters share the same nominal 3 arc-second spatial resolution as LandScan Mosaic but are offset in grid origin. As a result, GHSL cells do not map one-to-one onto LandScan Mosaic cells. LSM-TS aligns GHSL values to the LandScan Mosaic grid through an aggregation step after temporal interpolation.

Temporal interpolation of built-surface area

GHSL-BUILT-S estimates are available at 5-year reference epochs. Let G_{i,j,t_k} denote the GHSL-BUILT-S area for GHSL cell (i, j) at reference year t_k, where $t_k \in \{1975, 1980, \ldots, 2025\}$. Annual built-surface values are estimated through pixel-wise linear interpolation between consecutive GHSL epochs. For a year t such that $t_k \leq t \leq t_{k+1}$:

$$G_{i,j,t} = G_{i,j,t_k} + \left(\frac{t - t_k}{t_{k+1} - t_k} \right) \left(G_{i,j,t_{k+1}} - G_{i,j,t_k} \right). \tag{5}$$

Interpolation is applied independently to each GHSL cell. Interpolated values are constrained to be non-negative; any negative artifacts are truncated to zero. This produces an annual built-surface time series from 1975 through 2024 for subsequent scaling.

Aggregation of GHSL to the LandScan Mosaic grid

Because the GHSL and LandScan Mosaic grids differ in origin, each LandScan Mosaic cell overlaps four GHSL cells. Let $G^{(q)}_{r,c,t}$ denote the temporally interpolated GHSL-BUILT-S value for quadrant $q \in \{\mathrm{NW}, \mathrm{NE}, \mathrm{SE}, \mathrm{SW}\}$ overlapping LandScan Mosaic cell (r, c) in year t. The annual GHSL value assigned to the LandScan Mosaic cell is computed as the arithmetic mean of the four overlapping quadrant values:

$$G_{r,c,t} = \frac{1}{4} \sum_{q \in \{\mathrm{NW},\mathrm{NE},\mathrm{SE},\mathrm{SW}\}} G^{(q)}_{r,c,t}. \tag{6}$$

This step produces one annual built-surface estimate for each LandScan Mosaic cell while preserving consistency with the output raster geometry. The GHSL-BUILT-S inputs and LandScan Mosaic rasters are both stored in EPSG:4326 on nominal 3 arc-second grids, with an angular cell size of 1/1200 degrees. Comparison of the 2024 LandScan Mosaic affine transform with representative raw GHSL production tiles confirmed a constant half-cell offset between the two grids: 0.5 cell widths in longitude and 0.5 cell heights in latitude. This offset places each LandScan Mosaic cell over four GHSL cells with equal overlap fractions of 0.25 for the northwest, northeast, southwest, and southeast quadrants. We therefore used an unweighted arithmetic mean of the four overlapping GHSL quadrant values in Equation (6).

Derivation of annual scaling factors

For each LandScan Mosaic cell (r, c) and year t, LSM-TS computes a built-surface scaling factor relative to the interpolated 2024 GHSL value. Let $G_{r,c,2024}$ be the aggregated GHSL-BUILT-S value in the baseline year. The scaling factor is defined as:

$$C_{r,c,t} = \begin{cases} 1, & G_{r,c,2024} = 0, \\ \dfrac{G_{r,c,t}}{G_{r,c,2024}}, & G_{r,c,2024} > 0. \end{cases} \tag{7}$$

The interaction between the 2024 LandScan Mosaic baseline population value and the 2024 aggregated GHSL-BUILT-S value is summarized in Table 2. Because the historical adjustment is multiplicative, cells with zero 2024 LandScan Mosaic population remain zero in all historical backcast layers, even when the aggregated GHSL-BUILT-S value is nonzero. Conversely, cells with positive 2024 LandScan Mosaic population but zero aggregated GHSL-BUILT-S receive a scaling factor of 1 before ADM1 normalization, so their preliminary historical values retain the 2024 baseline value prior to administrative normalization.

Adjustment of the 2024 ambient population baseline

Let $P_{r,c,2024}$ denote the 2024 LandScan Mosaic ambient population estimate for LandScan Mosaic cell (r, c). The preliminary unnormalized LSM-TS estimate for year t is:

Table 2. Decision logic for zero 2024 population and zero 2024 built-surface cases. The table describes how the preliminary unnormalized historical estimate is computed before ADM1 normalization.

2024 LandScan Mosaic population	2024 aggregated GHSL-BUILT-S	Scaling rule	Preliminary historical estimate
$P_{r,c,2024} = 0$	$G_{r,c,2024} = 0$	$C_{r,c,t} = 1$	$\tilde{P}_{r,c,t} = 0$ for all historical years
$P_{r,c,2024} = 0$	$G_{r,c,2024} > 0$	$C_{r,c,t} = G_{r,c,t}/G_{r,c,2024}$	$\tilde{P}_{r,c,t} = 0$ for all historical years because the baseline population is zero
$P_{r,c,2024} > 0$	$G_{r,c,2024} = 0$	$C_{r,c,t} = 1$	$\tilde{P}_{r,c,t} = P_{r,c,2024}$ before ADM1 normalization
$P_{r,c,2024} > 0$	$G_{r,c,2024} > 0$	$C_{r,c,t} = G_{r,c,t}/G_{r,c,2024}$	$\tilde{P}_{r,c,t} = P_{r,c,2024} \cdot C_{r,c,t}$ before ADM1 normalization

$$\tilde{P}_{r,c,t} = P_{r,c,2024} \cdot C_{r,c,t}. \tag{8}$$

Cells with zero baseline population remain zero for all years. This adjustment preserves the 2024 fine-scale ambient population pattern while modulating cell-level values according to the GHSL-BUILT-S trajectory.

Normalization to administrative population targets

All annual preliminary surfaces from 1975 through 2024 are normalized to annual ADM1 target populations. The ADM1 targets are derived from LandScan Global subnational trajectories and scaled within each country-year so that their sums equal the corresponding U.S. Census Bureau International Database national population total. Thus, the Census Bureau provides the national control total, whereas the relative allocation among ADM1 units is derived from the bounded subnational trajectories described above.

For 2024, the LandScan Mosaic surface supplies the preliminary within-ADM1 spatial pattern, which is adjusted by a constant factor within each ADM1 unit to match its 2024 target. Let a index ADM1 units, and let $T_{a,t}$ denote the final country-year-normalized target population for administrative unit a in year t, as defined in Equation 4:

$$S_{a,t} = \sum_{(r,c)\in a} \tilde{P}_{r,c,t}. \tag{9}$$

Final normalized cell values are then calculated as:

$$\hat{P}_{r,c,t} = \tilde{P}_{r,c,t} \cdot \frac{T_{a,t}}{S_{a,t}}, \qquad (r,c) \in a. \tag{10}$$

Equation 10 is applied for ADM1-year units with $S_{a,t} > 0$. ADM1-year units with positive target population and zero preliminary population provide no valid within-unit allocation support and were flagged during production. Released rasters were required to pass administrative control-total checks after normalization.

The final normalized output preserves the relative spatial pattern of the preliminary estimates within each ADM1 unit while matching the final country-year-normalized ADM1 targets. Because those ADM1 targets are scaled to authoritative national totals before raster normalization, the workflow preserves national population controls by construction and then evaluates raster-level recovery of the ADM1 targets after output generation.

Output generation

The workflow produces 50 normalized annual ambient population rasters covering 1975 through 2024. The 1975–2023 layers are historical backcasts derived from the 2024 spatial baseline and annual GHSL-BUILT-S change, while the 2024 layer retains the baseline's within-ADM1 spatial pattern before being normalized to the 2024 ADM1 targets. Every released annual raster therefore conforms to the same country-year national control-total framework.

Data Records

The LSM-TS v1.0 release consists of 50 annual global ambient population rasters covering 1975 through 2024[26]. The version-of-record Cloud Optimized GeoTIFF files are distributed through the LandScan data portal at `https://landscan.ornl.gov` and are identified by DOI `https://doi.org/10.48690/lsm/zew2-1n91`. Each file contains one global raster for one year and may be downloaded independently. The data are also available as an image collection for cloud-based visualization and analysis through the Google Earth Engine Community Catalog at `https://gee-community-catalog.org/projects/landcast/`.

Annual raster files

Each annual raster is distributed as a single-band Cloud Optimized GeoTIFF. Cell values represent estimated ambient population counts per 3 arc-second grid cell. Values are counts per grid cell, not population density. The released files cover 50 annual time steps from 1975 through 2024.

The Cloud Optimized GeoTIFF format (COG) was selected to support efficient access to large raster files. COGs organize GeoTIFF data using internal tiling, overviews, and byte-range-readable structure so that software can retrieve only the portions of a file needed for visualization or analysis rather than requiring full-file download[27]. This structure is well suited to annual global rasters distributed as individual files.

The file naming convention is:

```
landscan_mosaic_timeseries_<year>.tif
```

where `<year>` is an integer year from 1975 to 2024. For example:

```
landscan_mosaic_timeseries_1975.tif
landscan_mosaic_timeseries_2000.tif
landscan_mosaic_timeseries_2024.tif
```

Versioning

This Data Descriptor describes LandScan Mosaic Time Series v1.0, which is anchored to the 2024 LandScan Mosaic ambient population surface and provides annual rasters for 1975–2024. Version 1.0 is a fixed release associated with DOI: `https://doi.org/10.48690/lsm/zew2-1n91`. Future releases may update the baseline year, extend the time series, incorporate revised input datasets, add additional population concepts, or modify methodological components. Because future releases may regenerate the full historical series rather than only add new years, each future release will receive a distinct version identifier and, where applicable, a distinct DOI. Version 1.0 files will remain accessible through the product landing page after subsequent versions are released.

Technical Validation

Technical validation was designed to assess whether the released LSM-TS rasters are internally consistent, preserve the intended administrative population controls, maintain a stable grid structure across years, and produce plausible spatial and temporal population patterns. Because no independent global, historical, 3 arc-second reference dataset exists for ambient population, validation was implemented as a set of complementary diagnostics rather than as a single definitive cell-level accuracy assessment. The checks included raster integrity and grid-consistency tests, administrative control-total recovery, an independent ADM2 benchmark against administrative population totals, temporal and spatial plausibility review, and manual visual inspection.

Validation of gridded population products is inherently scale-, reference-, and use-case-dependent. Previous evaluations have shown that product agreement varies by population density, settlement type, geography, reference data, population concept, and modeling approach, and that no single gridded population product performs best across all settings[1,6,28,29]. Validation results should therefore be interpreted as evidence about specific dimensions of product behavior rather than as a definitive cell-level accuracy estimate. For this reason, the LSM-TS validation combines internal grid and control-total checks, independent subnational agreement assessment, and temporal-spatial plausibility diagnostics.

ADM1 target construction diagnostics

The ADM1 target trajectories are intermediate normalization inputs rather than independent validation data. Production diagnostics were used to characterize the target-construction procedure, including fitted ADM1 trend slopes, lower-bound effects, and country-year scaling factors used to match national control totals. These diagnostics provide context for interpreting the derived ADM1 targets, particularly for small administrative units, units with declining fitted trends, and countries requiring larger national scaling adjustments.

Across 3,423 country-ADM1 units in 263 countries and areas, the median fitted annual ADM1 slope was 3,335.93 persons per year, with an interquartile range of -18.65 to 17,151.70 persons per year. Expressed relative to the mean observed 2000–2024 ADM1 population, the median fitted annual change was 0.97% per year, with an interquartile range of -0.10% to 2.21% per year. Negative fitted slopes occurred in 919 ADM1 units (26.85%), while positive fitted slopes occurred in 2,487 ADM1 units (72.66%).

The lower-bound rule affected 760 ADM1 units (22.20%) in at least one pre-2000 year and 10,949 ADM1-year target records (6.53%) across 1975–2023. Population-weighted lower-bound effects represented 0.35% of ADM1 target person-years, indicating that the rule primarily affected small or declining units. The country-year scaling factor in Equation (4) had a median value of 1.0044, with a 1st–99th percentile range of 0.2026–4.6210. Scaling factors ranged from 0.0700 to 9.8840 across all country-year records.

Administrative control-total recovery

Control-total enforcement and independent geographic reaggregation were evaluated separately. During normalization, raster cells were scaled using the production ADM1 cell assignments described in Methods. Sums calculated from those assignments recover the corresponding ADM1 targets apart from floating-point rounding. After the rasters were written and converted to Cloud Optimized GeoTIFFs, they were independently reaggregated using the vector ADM1 geography and a separate zonal-statistics workflow.

The residuals reported below therefore measure agreement between the production targets and this independent vector-based reaggregation. They reflect differences in rasterization, coastline treatment, edge-cell inclusion, nearest-feature assignment, and administrative crosswalk matching; they do not represent population removed during normalization. These effects are most apparent for small islands, special territories, and units with limited raster support.

Across 166,551 positive-target ADM1-year checks, the independently reaggregated LSM-TS zonal sum divided by the corresponding production target was 0.998297. The median ADM1-year absolute percent residual was 0.0148%, and the population-weighted mean absolute percent residual was 0.2106%. Annual population-weighted residuals ranged from 0.1287% to 0.3355%. A total of 70.5%, 87.5%, and 91.7% of ADM1-year checks were within 0.1%, 0.5%, and 1% of their targets, respectively.

The largest percentage residuals were concentrated in small-island and special-territory units with very small populations or sparse raster support. These cases have limited influence on population-weighted metrics but are retained in the validation tables to document known edge cases in applying vector administrative geometries to a fixed 3 arc-second raster grid. Figure 3 summarizes the distribution of ADM1-year residuals and the agreement between annual ADM1 target totals and raster-derived ADM1 zonal totals.

Table 3. Administrative control-total recovery under independent vector-based zonal aggregation, 1975–2024. Annual normalized rasters were independently reaggregated using the fixed vector ADM1 geography and a separate zonal-statistics workflow, then compared with the production ADM1-year targets.

Metric	**Value**
Years evaluated	1975–2024
Target ADM1 units	3,423
Matched ADM1 units after crosswalk repair	3,422
Matched target population person-years	99.9991%
Positive-target ADM1-year checks	166,551
Independent zonal sum/production target total ratio	0.998297
Median absolute percent residual	0.0148%
Population-weighted mean absolute percent residual	0.2106%
Annual weighted residual range	0.1287–0.3355%
ADM1-year checks within 0.1%	70.5%
ADM1-year checks within 0.5%	87.5%
ADM1-year checks within 1%	91.7%

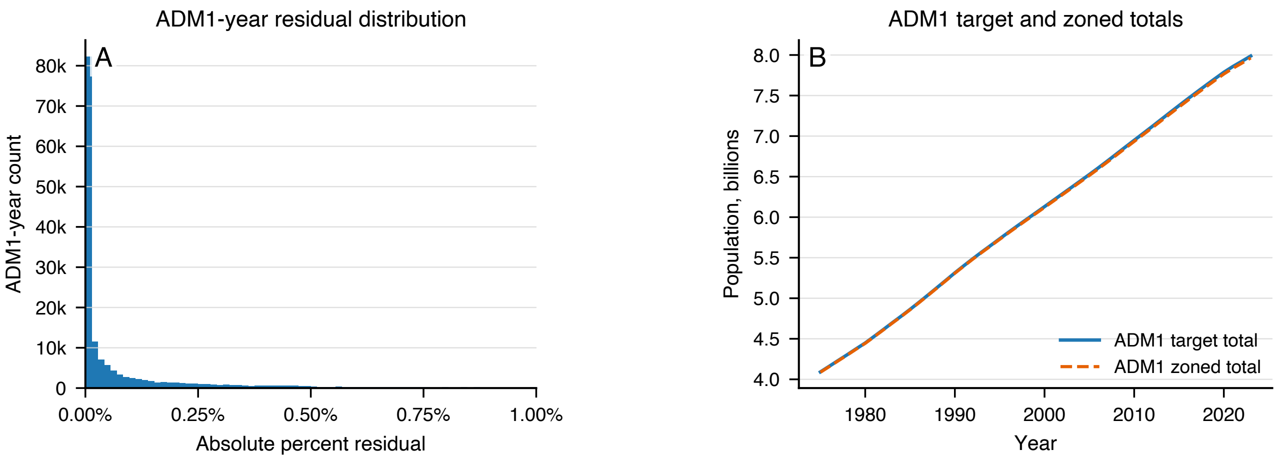

Figure 3. Administrative control-total recovery under independent vector-based zonal aggregation, 1975–2024. Annual normalized LandScan Mosaic Time Series rasters were independently reaggregated using the fixed vector ADM1 geography and a separate zonal-statistics workflow, then compared with the production ADM1 target populations. Panel A shows the distribution of ADM1-year absolute percent residuals for values below 1%. Panel B compares annual production ADM1 target totals with totals obtained through independent zonal aggregation. Across 166,551 positive-target ADM1-year checks, the median absolute percent residual was 0.0148%, and the population-weighted mean absolute percent residual was 0.2106%. These residuals reflect differences between the production cell assignments and independent vector-based aggregation, including rasterization, coastline treatment, edge-cell inclusion, and administrative crosswalk matching; they do not indicate failure of the production normalization procedure.

Independent ADM2 benchmark

An independent subnational benchmark was conducted using U.S. Census Bureau Subnational Population Estimates and Projections and their linked digital administrative boundary files[30]. The Census Bureau produces subnational estimates and projections for selected countries from 2000 onward, with temporal coverage and administrative level varying by country. These estimates are designed to be consistent with national projections from the U.S. Census Bureau International Database. For the present benchmark, reference records corresponding to second-level administrative units were matched to their associated Census Bureau boundary files. LSM-TS rasters were independently aggregated to those boundaries and compared with the corresponding reference totals for overlapping countries and years. Valid comparisons required a positive reference population. The benchmark is independent of the LandScan Global-derived ADM1 trajectories used for normalization, although both the benchmark and the LSM-TS national controls are aligned with Census Bureau national projections.

This comparison evaluates agreement with independent subnational population totals, but it is not a direct cell-level validation of ambient population. The reference totals represent administrative residential population counts, whereas the LSM-TS represents ambient population, or the estimated spatial distribution of people over a typical 24-hour period. Consequently, close agreement with residential ADM2 totals is not necessarily expected at fine spatial scales, particularly in areas where commuting, institutional populations, tourism, displacement, work sites, transport nodes, or other nonresidential activity patterns redistribute people away from their place of residence. Differences therefore reflect population concept, input data, boundary alignment, spatial allocation, and other modeling differences.

Three comparison modes were evaluated. First, native ADM2 zonal sums were compared directly with the ADM2 reference totals. Second, estimates were rescaled within each country-year so that each product's country-year total matched the corresponding reference total before ADM2 errors were recomputed. Third, where ADM1 identifiers were available, estimates were rescaled within ADM1-year groups before comparison with ADM2 totals. The country-year rescaled comparison separates within-country spatial allocation differences from national total differences, while the ADM1-year rescaled comparison focuses more directly on allocation among ADM2 units nested within the higher-level administrative geography.

Native LSM-TS ADM2 estimates showed broad agreement with the independent ADM2 reference totals. Across valid ADM2-year observations, the native product/reference total ratio was 1.022, the median absolute percent error was 11.30%, the population-weighted mean absolute percent error was 21.41%, and the Pearson correlation on log-transformed ADM2 population totals was 0.973. Country-year rescaling produced little change in the error metrics, indicating that discrepancies were not primarily caused by national-scale total population differences. ADM1-year rescaling modestly improved the population-weighted mean absolute percent error to 19.95%, suggesting that some remaining disagreement reflects allocation within higher-level administrative units.

The native ADM2 WMAPE of 21.41% should therefore be interpreted as a subnational agreement metric against residential administrative totals, not as a direct estimate of fine-scale ambient population accuracy. For context, complete-case comparisons over 30,688 ADM2-year records for which LSM-TS, WorldPop, and GHS-POP[8,9] were all available produced WMAPE values of 22.36%, 12.37%, and 11.82%, respectively. These comparisons are reported as contextual benchmarks rather than as a ranking of product accuracy because the products differ in population concept, temporal coverage, spatial resolution, modeling design, and relationship to residential administrative totals.

Agreement varied across countries and ADM2 population sizes. Population-weighted metrics were emphasized when summarizing agreement in terms of represented population, while unweighted metrics were retained to characterize small-area behavior. These comparisons should be interpreted as administrative-scale agreement diagnostics rather than as cell-level validation or a ranking of product accuracy.

Table 4. Independent ADM2 benchmark against U.S. Census Bureau Subnational Population Estimates and Projections. Metrics summarize LSM-TS agreement with ADM2 reference totals under native, country-year rescaled, and ADM1-year rescaled comparison modes. APE denotes absolute percent error and WMAPE denotes population-weighted mean absolute percent error.

Comparison mode	Product/reference ratio	Median APE	WMAPE	log1p Pearson r
Native	1.022	11.30%	21.41%	0.973
Country-year rescaled	1.000	11.27%	21.34%	0.976
ADM1-year rescaled	1.000	10.74%	19.95%	0.977

Temporal and spatial plausibility review

Temporal plausibility checks evaluated whether annual population trajectories were internally consistent and free of obvious processing artifacts. Annual raster totals, ADM1 totals, country totals, and selected regional summaries were reviewed through time. Additional country-level animations were generated from the annual raster series and inspected to identify missing frames, abrupt year-to-year changes, unexpected spatial redistribution, duplicated panels, geography mismatches, and disagreement between mapped population patterns and accompanying trend lines.

Quantitative temporal integrity checks were computed from ADM1-zoned annual totals for the complete 1975–2024 series. These checks compare annual raster-derived ADM1 sums with the production targets and summarize year-to-year behavior after raster writing and independent re-aggregation. Because all annual rasters are normalized to administrative controls, these are internal consistency diagnostics rather than independent accuracy tests.

Table 5. Temporal integrity diagnostics from ADM1-zoned annual totals. Diagnostics summarize control-total recovery and year-to-year changes across the complete normalized 1975–2024 series.

Diagnostic	Value
Years evaluated for normalized release period	1975–2024
Median absolute percent difference between global ADM1-zoned and target totals	0.1417%
Maximum absolute percent difference between ADM1-zoned and target totals	0.2916% in 2023
Median absolute year-to-year change in ADM1-zoned global total	1.2966%
Maximum absolute year-to-year change in ADM1-zoned global total, 1975–2024	1.8346% in 1980–1981

Manual review focused on four checks: temporal continuity, spatial reasonableness, panel and geography consistency, and trend coherence. The annual surfaces generally showed smooth temporal change, stable settlement patterns, and expected concentration of higher population densities in established urban areas and settlement corridors. Spatial plausibility was assessed by examining whether population remained concentrated in plausible settlement areas rather than being uniformly redistributed across administrative units. Diagnostics included visual review of urban regions, rural settlement regions, small islands, coastal areas, and regions with rapid built-environment change. Additional concentration checks compared cell-level population concentration within ADM1 units against a uniform ADM1 redistribution baseline. These checks are interpreted as plausibility diagnostics rather than independent accuracy validation, because the historical surfaces are modeled reconstructions informed by built-surface change and administrative controls rather than direct historical observations at grid-cell scale.

Known limitations

Several limitations should be considered when interpreting the validation results and reusing the dataset. First, there is no independent global historical reference dataset for ambient population at 3 arc-second resolution. Most available population reference data are residential, administrative, or available only for selected countries and years.

Second, the 1975–2023 layers are historical backcasts, whereas the 2024 LandScan Mosaic surface provides the fine-scale spatial baseline. The released 2024 layer is not an unchanged copy of that baseline: its values are multiplied by ADM1-specific factors so that the resulting administrative totals conform to the same country-year control framework applied to the historical layers. Consequently, users requiring the original, unnormalized 2024 LandScan Mosaic product should obtain and cite that product separately.

Third, pixel-level historical change is driven by built-surface change and administrative population controls, not by direct historical observations at each grid cell. The backcast layers are constrained by the positive-population support of the 2024 LandScan Mosaic baseline. Cells with zero population in the 2024 baseline remain zero in all earlier years, so the dataset cannot independently represent historically populated locations that are absent from the 2024 baseline. This limitation is most relevant for local-scale analyses, areas with substantial settlement abandonment or relocation, and places where historical population support differs from the 2024 baseline.

Fourth, GHSL-BUILT-S is used as a proxy for changes in population support, but built surface does not directly observe occupancy, building height, residential use, household size, vacancy, commuting, or temporary displacement[16,22]. These factors are represented only indirectly through the 2024 LandScan Mosaic baseline, the built-surface trajectory, and the administrative controls. These limitations are especially relevant in sparse, rural, or rapidly changing settlement contexts where built-environment indicators, census geography, and actual population presence may be weakly aligned. Validation studies have shown that gridded population agreement varies by geography, population density, reference data, and product design[6,28]. Users conducting local-scale analyses in such settings should interpret cell-level estimates cautiously and, where possible, compare results with independent local information or aggregate to spatial units appropriate for the application.

Fifth, the fixed administrative geography supports temporal consistency but does not reconstruct historical boundary changes. Country boundaries follow an LSIB-aligned representation, and ADM1 units follow the harmonized subnational boundary geography used for this release. Annual targets are therefore expressed on a fixed reference geography rather than on historical administrative boundaries.

The ADM1 target trajectories are modeled rather than directly observed annual demographic series. They were constructed by fitting first-order trends to LandScan Global-derived ADM1 estimates for 2000–2024, extrapolating those trends to earlier years, applying the lower-bound rule described in Methods, and rescaling the resulting subnational distributions to annual International Database national totals. This approach imposes smooth subnational trajectories and cannot reproduce nonlinear regional demographic change, abrupt displacement, or historical changes in administrative geography. The linear fitting step reduces year-specific variation among the source LandScan Global releases but does not remove dependence on those inputs.

The lower-bound rule prevents negative or implausibly small extrapolated values but imposes an additional constraint on small or declining administrative units. Accordingly, pre-2000 ADM1 targets and the spatial surfaces normalized to them should be interpreted as model-based historical reconstructions rather than direct observations of subnational population.

Overall, the LSM-TS should be interpreted as a spatially consistent annual reconstruction of ambient population distribution rather than as a direct observation or causal demographic model. The validation results demonstrate internal consistency, preservation of imposed ADM1 controls, broad agreement with independent ADM2 administrative totals, and plausible spatial-temporal behavior, while also documenting known edge cases and limitations relevant to reuse.

Usage Notes

Users should interpret the LSM-TS as a model-based annual reconstruction of ambient population distribution from 1975 through 2024. Users aggregating the rasters to administrative units should note that the released time series was normalized and validated using the fixed ADM1 geography described in Methods; results aggregated to other boundary vintages or alternative administrative datasets may differ because of boundary alignment, coastline treatment, and raster-cell assignment.

Cell values represent estimated persons per grid cell, not density. Users conducting zonal statistics should report the product version, year or years analyzed, population concept, spatial aggregation procedure, and any treatment of coastal cells, water cells, NoData values, or masks. Users comparing the dataset with residential population products or census counts should explicitly note the difference between ambient and residential population concepts. Zero-valued cells are valid estimates of no ambient population and should not be treated as missing data. Users should mask only the declared NoData value of -9999 unless they intentionally wish to exclude unpopulated cells.

The 2024 LSM-TS raster should not be treated as numerically identical to the source LandScan Mosaic 2024 raster. It preserves the source raster's relative spatial pattern within each ADM1 unit but has been normalized to the 2024 ADM1 targets. Users comparing the two products should therefore expect constant within-ADM1 adjustment factors.

For cloud-based use, the complete annual series is also available through the Google Earth Engine Community Catalog at `https://gee-community-catalog.org/projects/landcast/`. Users should consult that catalog record for the Earth Engine asset identifier, access example, pyramiding behavior, and catalog-specific assumptions and limitations.

Data Availability

The LandScan Mosaic Time Series, Version 1.0 annual ambient population rasters [26] are available through the LandScan data portal at `https://landscan.ornl.gov` and are identified by DOI `https://doi.org/10.48690/lsm/zew2-1n91`. The version-of-record release contains 50 individually downloadable annual Cloud Optimized GeoTIFF files covering 1975 through 2024.

The data are also available for cloud-based access through the Google Earth Engine Community Catalog at `https://gee-community-catalog.org/projects/landcast/`. The Community Catalog page supplies the Earth Engine asset identifier, access example, and catalog-specific assumptions and limitations. The DOI-identified LandScan release is the permanently cited version of record.

Code Availability

The authors are completing institutional review for public release of the repository. Following approval, and no later than publication, the repository will be released publicly and archived through a DOI-issuing repository. The public repository URL, archived release DOI, version, and software license will be added before final acceptance.

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Competing Interests

The authors declare no competing interests.

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