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Aligning emissions with decisionmaking: estimating urban contributions to global carbon dioxide emissions

Keywords: Urban emissions; urban-rural classification; urban climate mitigation and planning

Abstract

Urban areas are widely viewed as central to the global carbon challenge, yet estimates of the urban contribution to global CO_2 emissions vary substantially because studies define "urban" and allocate emissions using different boundaries and accounting perspectives. We address this challenge by introducing a globally consistent, administrative-boundary framework that aligns emissions with governance units and distinguishes urban centres, peri-urban areas, and rural areas across all subnational administrative divisions worldwide. This governance-aligned classification provides a consistent basis for urban emissions typologies, enabling comparable urban emission quantification across regions and accounting perspectives. Combining high-resolution territorial emissions inventories (EDGAR, ODIAC, CEDS) with global consumption-based footprints (GGMCF), we estimate that in 2022 urban jurisdictions (urban centres + peri-urban areas) account for 72-76% of global territorial CO_2 emissions, with urban centres contributing 30-37% and 39-42% from peri-urban areas. Using consumption-based data, we estimate that urban areas account for ~82% of CO_2 emissions in 2015. We further show that the sectoral composition of urban territorial emissions has shifted from 1970 to 2022, with the energy sector increasing in prominence and relative contributions from buildings and industry declining. Finally, comparing territorial and consumption-based estimates across subnational units, we map consumption–production imbalances and find that 63% of regions are net embodied-emissions importers. These results provide a critical update to global assessments of urban emissions and demonstrate the value of pairing territorial and consumption-based accounting on governance-relevant boundaries for interpreting responsibility and identifying mitigation leverage points.

1. Introduction

Subnational and non-state actors, particularly cities, play a crucial role in mitigating climate change and reducing greenhouse gas (GHG) emissions,[1,2] yet estimates of their contributions to global emissions are inconsistent. Existing studies report a wide range of "urban contributions," from as low as 40%[3] to as high as between 71-76%,[4] largely due to the fact that studies define and operationalize urban definitions, boundaries and emissions accounting in fundamentally different ways. Some studies base emission estimates on physical measures of built-up urban extent;[5–7] while others treat them as functional urban systems tied to consumption energy demand and infrastructure,[8] or as administrative jurisdictions that map more directly onto governance and policy authority. Some account for territorial emissions (i.e., emissions resulting from activities occurring within a city boundary, production-based accounting), while others take a more holistic or systems-based approach and base quantification on consumption-based emissions. These choices substantially change which activities and emissions are counted as "urban," as well as the implied magnitude of urban responsibility. As a result, urban typologies used to compare cities, identify archetypes, and tailor mitigation strategies can become misleading when they are derived from inconsistent urban definitions and mixed accounting perspectives.

These distinctions matter because quantifying urban emissions is important to answer distinct questions that are often conflated in both the academic literature and policy practice: where emissions occur, which jurisdictions have the authority to act, and who drives emission through demand. Confusion arises when estimates produced under one definition (e.g., settlement footprints) are interpreted as another (e.g., jurisdictional responsibility), producing non-comparable “urban shares” and biasing conclusions about mitigation responsibility and potential.[9–12] Administrative-boundary accounting is necessary when the objective is to align emissions estimates with the governance units responsible for mitigation. Settlement-footprint methods describe emissions in dense cores but can undercount jurisdictional emissions by excluding sources located within urban administrative areas but outside dense “urban centre/cluster” pixels (Figure S1), especially in peri-urban zones and along infrastructure corridors. Because many policy-relevant sources (e.g., industrial areas, transport/logistics networks, ports/airports, and sometimes power generation) are spatially extensive and often sited outside dense cores, boundary choice can materially change estimated urban shares even when jurisdictional authority is unchanged. Interpretable assessments therefore require pairing governance-relevant boundaries with explicit accounting frames: territorial emissions capture within-boundary sources most directly shaped by local policy (e.g., land-use/buildings, transport, permitting), whereas consumption-based emissions attribute supply-chain (embodied) emissions to final demand within the jurisdiction, capturing how urban consumption drives emissions beyond local boundaries.

Here, we provide the first globally consistent, administrative-boundary estimates of urban contributions to global CO_2 emissions under both territorial and consumption-based accounting, with sector-resolved, time-varying results for territorial emissions. We draw from four publicly available and widely used datasets: the Emissions Database for Global Atmospheric Research (EDGAR),[13] the Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC),[14] and the Community Earth Atmospheric Data System (CEDS)[15] for territorial emissions and Moran et al.’s[16] consumption-based emissions accounting for more than 13,000 urban areas. Our contributions are threefold: first, we develop an urban-peri-urban-rural typology for Global Administrative Areas (GADM) Levels 1-5 by integrating statistical clustering approaches with multiple indicators of settlement intensity and human activity, enabling globally consistent and administratively coherent estimates of the urban contribution to both territorial and consumption-based emissions (see Methods). Second, we quantify long-run changes in urban territorial emissions and their sectoral composition. Third, we compute territorial–consumption gaps for all subnational units to develop a typology of net embodied-emissions importers and exporters (i.e., where consumption-based emissions exceed territorial emissions, and vice versa). Our governance-aligned integration provides a consistent empirical basis for emissions typologies across jurisdictions and for identifying mitigation leverage points that are often missed when relying on a single accounting lens.

2. Results

2.1 Urban contribution to global territorial emissions through a jurisdictional lens

We estimate that, in 2022, urban areas account for 72-76% of global territorial CO_2 emissions across three globally-available inventories, EDGAR, ODIAC, and CEDS (Table 1). Under our administrative-unit classification approach introduced in this paper, the range of urban contribution comprises a 30-37% emission contribution from urban centers and 39-42% from peri-urban areas (see Methods). These ranges reflect variability across underlying emissions datasets, while holding the jurisdictional accounting framework constant (Table 1). As a sensitivity check on how urban-peri-urban-rural definitions affect headline “urban contributions,” we also apply the GHS-DUC administrative-unit classification;[17] using the same inventories, it yields a higher urban share (80–83%; Table 1). The ~8-11 percentage-point difference underscores that global “urban contribution” estimates are urban-definition-sensitive even with identical emissions inputs and identical administrative boundaries. Our estimates are lower because our typology incorporates indicators beyond population (including economic activity and long-run built-up change), which can reassign heterogeneous and rapidly peri-urbanizing administrative units in an urban–peri-urban–rural classification (Figures S2–S3). Full details of the benchmark comparison and classification differences are provided in the Supplementary Information.

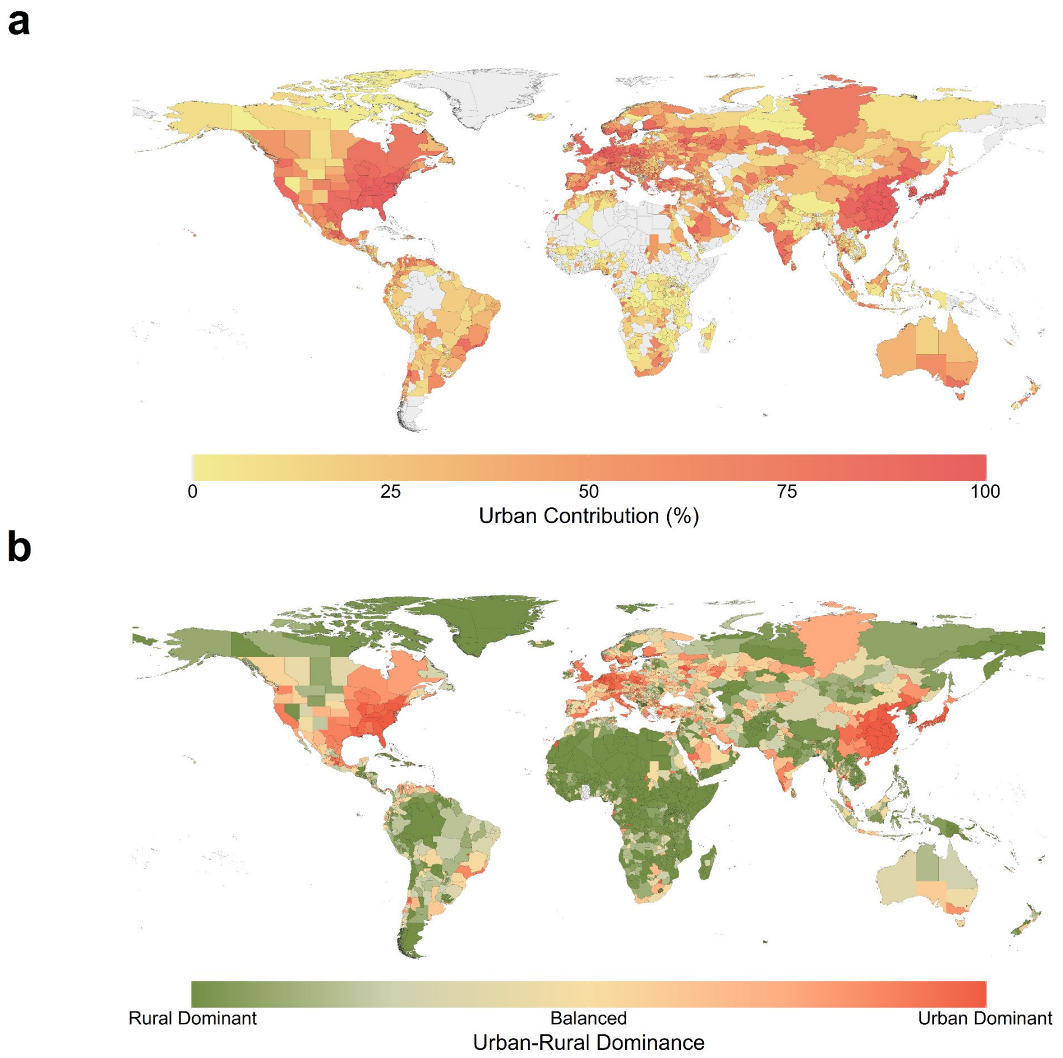

Figure 1. Urban contribution of territorial CO_2 emissions. **a,** the percentage of urban emissions for each administrative level 1 (Region); **b,** the relative dominance in the share of CO_2 emissions either from urban areas (Red), rural areas (Green), or their similar contributions (Balanced). The data source is the Emissions Database for Global Atmospheric Research (EDGAR).

Table 1. Urban-Rural Contribution to Global Territorial Emissions

	Urban-rural classification in this study			Urban-rural classification based on GHS-DUC[17]		
	Urban Center	Peri-urban Cluster	Rural Cluster	Urban Center	Peri-urban Cluster	Rural Cluster
Contribution to Global Territorial Emissions (%) (EDGAR in 2022)	29.9	42.5	27.7	33.5	45.9	20.5
Contribution to Global Territorial Emissions (%) (ODIAC in 2022)	37.2	38.6	24.2	42.6	40.4	17.0
Contribution to Global Territorial Emissions (%) (CEDS in 2022)	29.5	42.2	28.3	33.9	45.6	20.4

Note: Urban contribution represents the contribution of all urban areas (Urban Center + Peri-urban Cluster)

2.2 Spatial patterns of urban and rural emission contributions

The spatial distribution of urban and rural emission contributions highlights substantial geographic heterogeneity in where territorial CO_2 emissions are concentrated. Figure 1a shows the urban contribution (%) within each GADM level 1 unit (e.g., first-level administrative division, such as a state or province), while Figure 1b summarizes whether emissions are urban-dominant (shaded in red), rural dominant (shaded in green), or more balanced within the same administrative region. Across most high-income countries, including regions in the United States, Canada, Australia, Saudi Arabia, Japan, and EU member states, urban areas contribute the majority of territorial CO_2 emissions. In contrast, many low- and lower-middle-income countries exhibit a larger share of regions where rural contributions are comparable to or exceed urban contributions, including much of sub-Saharan Africa and parts of Southeast Asia and the Middle East. Upper-middle-income countries exhibit greater heterogeneity, with some regions where territorial emissions are primarily associated with urban areas and others where urban and rural contributions are of similar magnitude within the same country, as observed in Argentina, Brazil, and Indonesia. These patterns are consistent across the three territorial emission datasets (EDGAR, ODIAC, and CEDS) we evaluated, although the estimated urban contributions are systematically higher in ODIAC, followed by EDGAR and CEDS (Figure S4).

Importantly, regions classified as rural-dominant are not necessarily low-emitting regions, rather this pattern is consistent with territorial emissions being driven by spatially-extensive sources that are frequently located outside of dense urban centers (e.g., power generation, heavy industry, and major transportation corridors), even when these sources serve urban economic activity and household consumption. This distinction is consequential for mitigation planning, since urban-dominant regions may be more directly influenced by city and region-level policy instruments, whereas rural-dominant regions may require stronger sectoral interventions and coordination across administrative levels.

2.3 Sectoral evolution of urban territorial emissions

Using EDGAR territorial emissions and our urban–rural classification method, we analyze how the sectoral composition of urban territorial CO_2 emissions has evolved globally from 1970 to 2022, where “urban” includes both urban-center and peri-urban administrative units. To support interpretation from a mitigation-policy perspective, we aggregate EDGAR’s 27 sectors into 7 policy-relevant major categories: Energy, Industrial, Buildings, On-road Transport, Aviation & Shipping and Off-road Transport, Agriculture, and Waste (see Table S1).

Globally, urban territorial emissions have become increasingly concentrated in the energy sector. The Energy sector’s share of urban territorial emissions increased from 34% in 1970 to approximately 43% in 2022, peaking since the early 2000s (Figure 2a). Over the same period, Industry remained the second-largest contributor but changed relatively little in proportional terms (32% in 1970 to 30% in 2022), with minimal change since around 2010. The Buildings sector declined markedly from 20% in 1970 to 10% in 2022. Meanwhile, On-road Transport increased steadily from 10% in 1970 to 14% in 2022. The remaining sectors, including Aviation and Shipping and Off-road Transport, Agriculture, and Waste collectively contribute less than 5%.

Although the global sectoral profile appears relatively stable, these trends mask substantial cross-country divergence in where and how urban emissions are produced (Figure 2b). Rapidly developing economies show a pronounced increase in the urban Energy share, consistent with expanding electricity generation and energy supply to meet rising urban demand. In China, the share of urban territorial emissions from the Energy sector increased from 20% in 1970 to 48% in 2022. Similarly, in India, the Energy sector’s emission share rose from 28% to 40% over the same period. Conversely, the United States’ Industrial sector has declined from 28% to 13%, while Germany’s has fallen less from 30% to 19%. These divergent trajectories highlight that similar “urban contributions” can correspond to fundamentally different sectoral mitigation priorities, suggesting that urban climate strategies and benchmarks ideally should be interpreted through sectoral decomposition analysis.

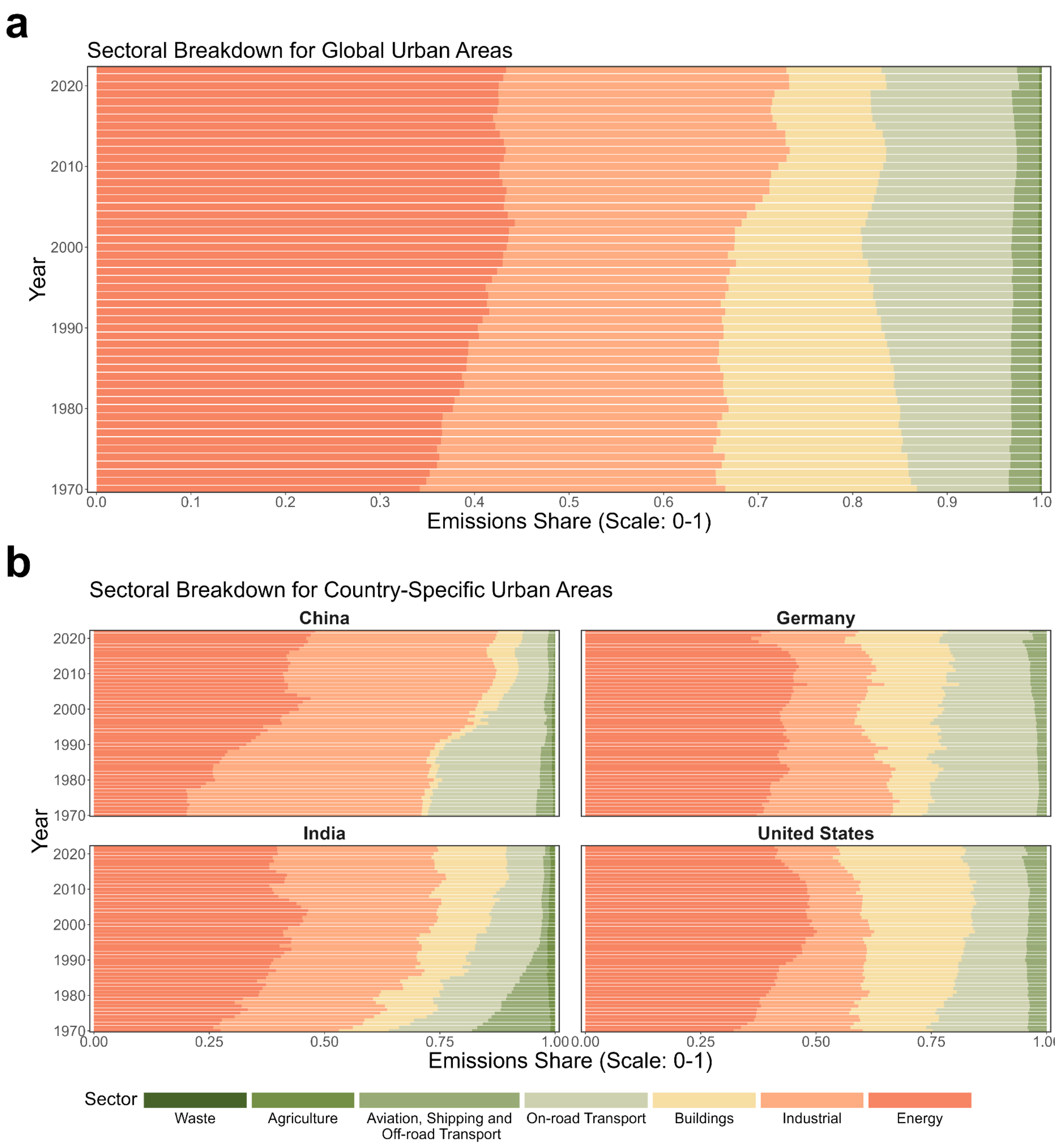

Figure 2. Sectoral breakdown of urban territorial CO_2 emissions worldwide and in major countries from 1970-2022.

2.4 Production-consumption imbalances in urban carbon dioxide emissions: a typology

Territorial accounting locates emissions, but consumption-based accounting is critical for tracing the demand-side drivers of urban emissions and the supply-chain emissions induced beyond city boundaries.[16,18,19] Using the most recent available data from the Global Gridded Model of Carbon Footprints (GGMCF) and our urban-rural classification approach, we estimate that urban areas account for approximately 82% of global consumption-based CO_2 emissions in 2015, exceeding the 73-77% share of global territorial CO_2 emissions attributed to urban areas in the same year across EDGAR, ODIAC, and CEDS (Table S2 and Figure S5).

To quantify production-consumption imbalances, we compute the emissions gap for all subnational administrative units as $\Delta E = E_{consumption} - E_{territorial}$, where positive values indicate net embodied-emissions importers and negative values indicate net exporters.[20] Figure 3 maps these gaps on a logarithmic scale, while Figure S6 reports per-capita gaps. Export-oriented, production-intensive regions (e.g., parts of southeastern China) exhibit negative gaps, while high-consumption regions (e.g., California and New York State) exhibit positive gaps. Among urban areas, England (301 Mt), California (299 Mt), and New York State (221 Mt) have the largest positive gaps, whereas Hebei (–236 Mt), Jiangsu (–228 Mt), and Shandong (–225 Mt) show large negative gaps (Figure S7).

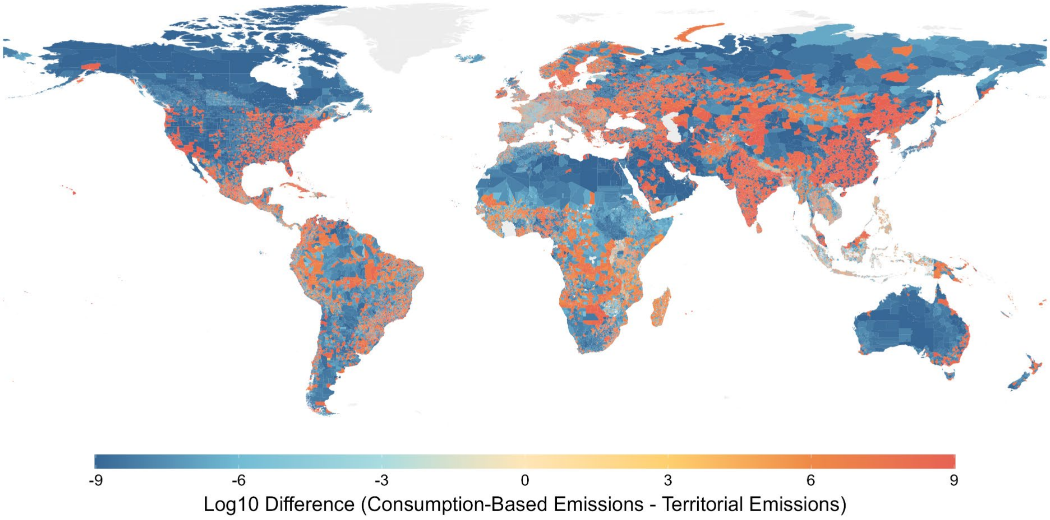

Figure 3. Emission gaps between consumption-based and territorial emissions across all subnational administrative areas worldwide. Note: The emission gap is calculated by consumption-based emissions minus territorial emissions. Regions in red indicate net importers, where consumption-based emissions exceed territorial emissions, while regions in blue represent net exporters, where territorial emissions surpass consumption-based emissions. Positive emission gaps are displayed on a logarithmic scale (log10), while negative emission gaps are transformed using the logarithm of their absolute values (log10) and then reassigned a negative sign.

We then relate these imbalances to longer-run decarbonization trajectories by estimating territorial emissions trends for each GADM level 1 unit using spline regressions around each region's peak year (Methods). Combining the direction of territorial change since 1970 (rising/declining/static) with importer/exporter status yields six typology categories (Figure 4a), highlighting where mitigation priorities may center on within-boundary reductions, demand-side measures, or both. Overall, 63% of regions are net embodied-emissions importers. Stratifying by income group reveals clear structure: regions that are rising and importing are concentrated in low- and lower-middle-income countries, whereas declining and importing regions are predominantly in upper-middle- and high-income countries (Figure 4b–c). Notably, many declining regions retain substantial positive gaps, indicating that territorial decarbonization can coexist with persistent demand-driven footprints embodied in supply chains.

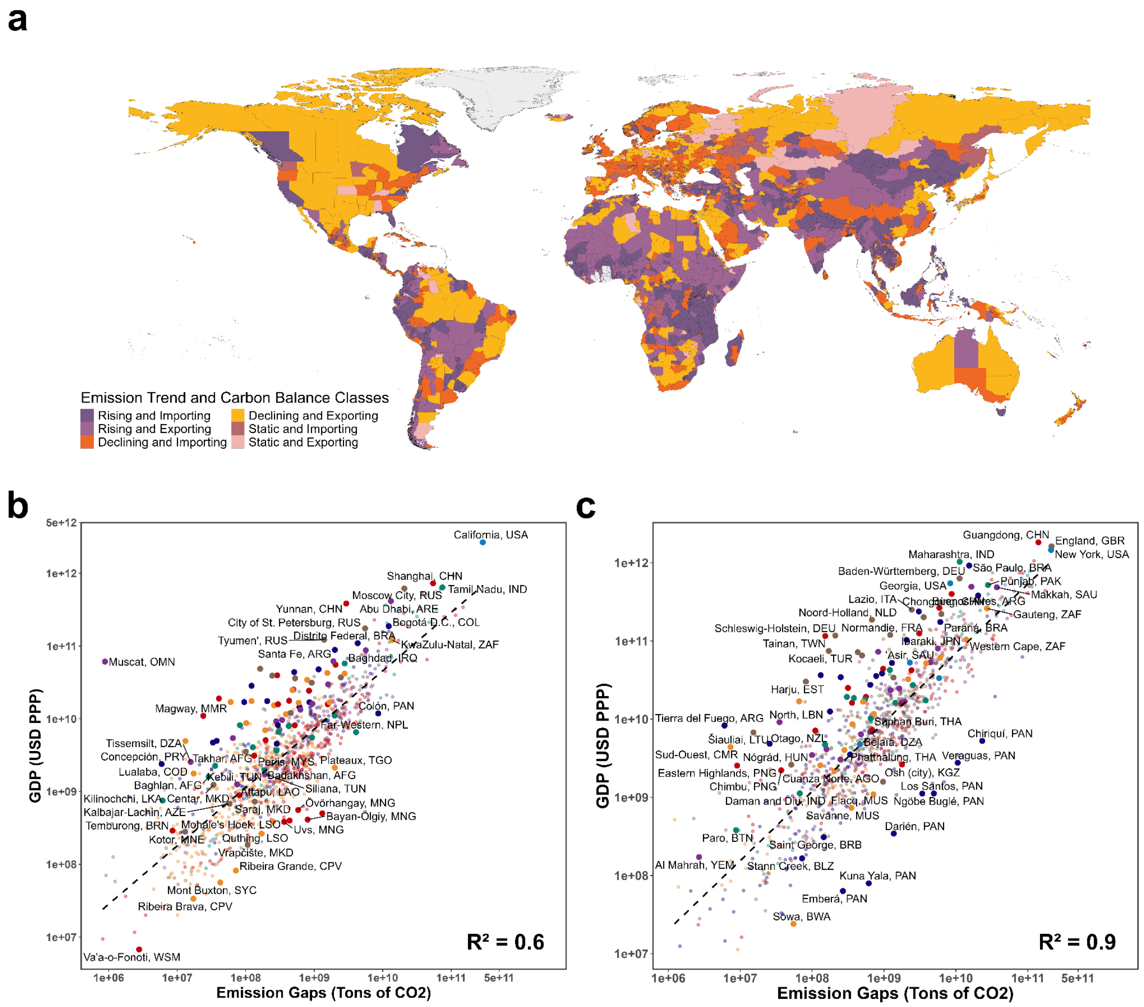

Figure 4. A typology of territorial emission trajectories and consumption-territorial emission gaps across subnational regions (1970-2022). Note: Panel (a) illustrates the trajectories of territorial emissions alongside the emission gaps between consumption-based and territorial emissions. The categories Rising, Declining, and Static denote increasing, decreasing, and stable trends in territorial emissions from 1970 to 2022, respectively. The labels Importing and Exporting indicate whether a region's consumption-based emissions exceed territorial emissions (Importing), or territorial emissions exceed consumption-based emissions (Exporting). Panel (b) shows the relationship between emission gaps and economic development levels for regions in the Rising and Importing category. Panel (c) shows the relationship between emission gaps and economic development levels for regions in the Declining and Importing category.

3. Discussion

This study advances understanding of cities' and urban areas' responsibilities for global climate action by providing the first globally consistent administrative-boundary accounting of urban, peri-urban, and rural CO_2 emissions, supported by a harmonized urbanization typology for administrative units. Existing global estimates often define "urban" using settlement-footprint or morphology-based delineations that describe where emissions occur relative to dense populated or built form but do not align with the jurisdictions through which targets are set, policies implemented, and accountability assessed. By classifying each administrative unit as an urban, peri-urban, or rural area, our approach captures emissions from peri-urban and infrastructure-related sources (e.g., industry, transport/logistics corridors, and in some contexts power generation) that frequently fall outside dense settlement pixels yet remain within governance units responsible for mitigation. Moreover, applying pixel-based typologies directly to heterogeneous administrative units can produce unstable classifications where large jurisdictions contain only small dense cores (Figure S3), motivating an updated administrative-unit typology that defines "urban" using multiple dimensions of human activity, rather than population density alone.

Using this classification, we provide a critical assessment of urban areas' contributions to global CO_2 emissions, showing that they contribute to 72-76% of global territorial CO_2 emissions in 2022 and ~82% of global consumption-based CO_2 emissions in 2015. For the first time, we also quantify the long-run sectoral evolution of urban emissions dating back from 1970 to 2022, showing a growing proportion of energy-sector emissions in cities and urban areas, a declining share from buildings and a rising proportion from transport. administrative units, we develop a typology showing that territorial decarbonization trajectories often tell only half the story: although 63% of subnational regions are net embodied-emissions importers, many regions with declining territorial emissions continue to exhibit persistent consumption–territorial gaps.

3.1 The need for greater national support for urban climate action

By aligning emissions accounting with decision-making boundaries, our analysis clarifies where mitigation responsibility is concentrated and where responsibility and capacity may be misaligned across governance levels. Across inventories, urban jurisdictions (cities and peri-urban zones) account for the majority of global CO_2 emissions under both territorial and consumption-based perspectives, placing them at the center of mitigation. Yet key determinants of these emissions, especially electricity supply, major transport infrastructure, and industrial development, are shaped by national regulation, investment, and planning, implying that urban mitigation cannot rely on municipal action alone.

This institutional reality helps explain why, despite growing momentum in subnational climate commitments, cities often struggle to translate plans into sustained emissions reductions.[21,22] Effective urban climate action requires more than local ambition -- tailored policies that address urban-specific sources of emissions, including energy systems, building stock, transportation infrastructure, and consumption patterns are needed.[23] Despite their centrality, cities are often sidelined in national climate strategies and reporting frameworks, which tend to rely on administrative boundaries and metrics that underestimate urban emissions or fail to capture interregional spillovers.

This misalignment is compounded by a lack of adequate financial and regulatory support from higher levels of government. Previous research has found that climate mitigation and adaptation activities account for less than 1% of spending in most U.S. state budgets, underscoring a persistent disconnect between local responsibilities and available resources.[24] Similarly, many of the most ambitious European cities pledging carbon neutrality struggle with even estimating basic financial costs of their decarbonization strategies.[25] In other cases, local governments lack control over key emission sources or the fiscal tools needed to act in what describe "governance-dependent ambition gaps," where these gaps prevent subnational actors from meeting their climate responsibilities without coordinated vertical support.[26]

Recent initiatives reflect growing recognition of this multi-level challenge. The Coalition for High Ambition Multilevel Partnerships (CHAMP) was launched at the 2023 COP28 in Dubai to emphasize the need for greater coordination and alignment in climate actions between national and local governments. Championed by the United Nations Framework Convention on Climate Change (UNFCCC), the initiative brings together over 60 countries and explicitly calls on national governments to include cities and regions in their climate plans (such as NDCs and long-term strategies), recognize their contributions, and provide enabling conditions, particularly through funding, capacity building, and legal frameworks that empower local action.[27]

3.2 Correcting emission blindspots in urban climate accountability

Our urban–peri-urban–rural typology highlights a systematic mismatch between where emissions occur territorially and where final demand is allocated in consumption-based accounts. Globally, 63% of subnational regions are net embodied-emissions importers (consumption-based emissions exceed territorial emissions), consistent with prior evidence that major cities' consumption-based footprints often exceed their territorial totals.[28] This pattern exposes a blind spot in territorial-only accounting: jurisdictions can register apparent progress in within-boundary inventories while remaining associated with large and sometimes persistent demand-driven footprints embodied in supply chains. Incorporating consumption-based perspectives therefore complements territorial accounting by revealing mitigation levers beyond conventional inventories, including procurement and purchasing standards, infrastructure investment choices, diet and mobility systems, and supply-chain engagement. The imbalance is especially pronounced in many high-income contexts, where territorial emissions may decline while consumption-based footprints remain high due to continued demand for emissions-intensive goods produced elsewhere, complicating climate accountability if progress is assessed only territorially.

Our typology also clarifies how these imbalances intersect with development trajectories. We observe decoupling consistent with structural change in several high-income settings (e.g., declining industrial shares in the United States and Germany) alongside rising energy- and industry-related emissions in rapidly developing economies (e.g., China and India). In parallel, 59% of regions classified as Rising and Importing are located in low- and lower-middle-income countries, concentrated in Africa and the Middle East, whereas 72% of Declining and Importing regions are in upper-middle- and high-income countries (e.g., the United Kingdom, France, Australia). These patterns are consistent with shifting production burdens along global supply chains and have equity implications: lower-income regions can bear the environmental costs of emissions-intensive production while higher-income regions retain consumption benefits.[29,30] Such displacement not only distorts the true sources of global emissions but also exacerbates climate injustice, as lower-income regions bear the environmental costs of production while high-income regions enjoy the benefits of consumption.[31] Incorporating consumption-based emissions into city-level and national climate planning ensures that climate accountability reflects the full carbon footprint of local demand, discourages emissions outsourcing, and supports more equitable and effective mitigation strategies across a globally interdependent economy.

3.3 Limitations

While our study advances a consistent framework and methodology to evaluate subnational contributions to global CO_2 emissions, several limitations remain. Although we find our administrative boundary-based approach yields robust and broadly consistent patterns across multiple globally gridded emission products, challenges still remain when using the GADM database for administrative boundaries. Administrative boundary resolution is uneven across countries in the GADM dataset, and the lowest consistently available level can be relatively coarse in some cases, such as in the United States, where the lowest-level administrative boundary available is at the county-level. This limitation hampers the ability to capture lower-level jurisdictions (e.g., cities and towns), where climate actions are frequently planned and implemented. In addition, our estimates remain sensitive to differences among gridded emission datasets in their sectoral allocation choices and in their ability to resolve emissions at the urban scales, notably for electricity-generation siting versus end-use. Because no single dataset perfectly represents urban emissions globally at a high resolution, we report ranges rather than a single definitive statistic to avoid false precision. Continued improvements in global emissions data, point-source characterization and subnational boundary standardization should reduce these uncertainties in future work.

Additionally, our analysis focuses exclusively on CO_2 emissions and does not include non-CO_2 greenhouse gases such as methane, which within cities is derived from waste[32] and may substantially alter the sectoral composition of emissions (see Figure S8). We focus on CO_2 to ensure comparability across the multiple datasets used in our study, some of which only measure CO_2, and to maintain consistency when pairing territorial inventories with available consumption-based footprints. This choice is further aligned with governance relevance, since beyond landfill and waste-related methane, mitigation options for many other non-CO_2 sources are frequently shaped by national regulation, agricultural systems, and industrial processes that are less directly controlled by municipal authorities. Future research should integrate non-CO_2 greenhouse gases to provide a more comprehensive assessment of urban emission sources and trajectories, particularly for Global South cities where waste-related methane emissions are significant contributors to urban areas' greenhouse gas profile.[33,34]

4. Methods

A key innovation we introduce in this paper is a globally consistent approach to identification of urban, peri-urban and rural administrative units using a statistical clustering approach[36] that classifies each administrative unit based on variables reflecting human settlement patterns, including the physical built environment and its long-term changes, population distribution, and economic activity proxied by GDP and electricity consumption. The resulting classification is then used to quantify urban contributions to global emissions–specifically, the share of global emissions attributable to urban areas, including both urban centers, defined as densely populated and urbanized settlements, and peri-urban clusters. Below we describe the datasets and the k-means procedure used to classify administrative units as urban centers, peri-urban, or rural.

4.1 Data sources

We integrate multiple high-resolution, spatially explicit datasets to quantify subnational territorial and consumption-based emissions. To characterize the degree of urbanization, we incorporate additional geospatial datasets, including gridded GDP (1990–2022, 30 arc-seconds),[37] GHS Population data (1975–2030, 100-meter resolution),[17] GHS Built-up surface data (1975–2030, 100-meter resolution),[38] and gridded electricity consumption (1992–2019, 1-kilometer resolution).[39] All spatial aggregations are conducted using cloud-based processing on Google Earth Engine, and administrative boundaries are standardized according to GADM v4.1, which delimits 356,508 administrative units across levels 0 to 5 globally. Further details and references for each dataset are provided in Table S3.

4.2 Urban-rural classification of administrative units

We use k-means clustering[36] to classify subnational administrative units in GADM version 4.1 at levels 1-5 as urban, peri-urban and rural. Our feature set captures multiple dimensions of settlement intensity and human activity (Figures S9–S10), including population size and density, built-up extent and long-term built-up change, economic activity proxied by GDP, and electricity consumption. We also include each unit's shares of national and regional totals to represent relative concentration within broader administrative contexts. The number of clusters is selected using an elbow (scree) criterion based on diminishing reductions in within-cluster variance.

To ensure scalability while retaining global heterogeneity, we implement a two-stage k-means procedure. First, we partition all administrative units into a large set of fine-grained micro-clusters and compute the median feature vector for each micro-cluster. We then re-cluster these micro-cluster medians into 100 subclusters using the same feature set. This design reduces computational burden while preserving structure in the high-dimensional feature space. We subsequently assign the 100 subclusters to three interpretable categories -- urban center, peri-urban cluster, and rural cluster -- based on their median profiles for core indicators, including urban built-up proportion, population density, electricity consumption, and GDP per capita (Figure S9). Finally, we apply targeted corrections for a small number of special-status jurisdictions (e.g., Washington, D.C.; Berlin; Oslo) to ensure appropriate classification given atypical administrative structures.

We then evaluate whether the resulting categories are statistically distinguishable. First, we apply permutational multivariate analysis of variance to test whether the multivariate feature distributions differ across the three categories. Results indicate strong separation ($p < 0.001$), supporting that the categories represent distinct groupings in the underlying feature space. Second, we use Kruskal–Wallis tests to compare the distribution of each feature across categories and identify the variables that most strongly differentiate the groups. Urban built-up proportion, population density, electricity consumption, and GDP per capita exhibit the strongest between-category differences (Table S4), providing empirical support for using these indicators as the primary basis for labeling and interpretation of the urban–peri-urban–rural typology.

As a benchmark and sensitivity check, we compare our administrative-unit typology with the GHS Degree of Urbanisation classification implemented on GADM units in the EU JRC Stage II analysis (GHS-DUC).[17] Details and comparative statistics are provided in the Supplementary Information (Figure S2; Table S2).

4.3 Trend estimation

Using annual territorial CO_2 emissions for 1970–2022, we estimate long-run trends with a piecewise linear specification on the log scale. Specifically, we model the logarithm of territorial CO2 emissions as a function of calendar year with a single spline knot at the year of peak emissions for each administrative unit, allowing separate linear slopes before and after the peak. For analyses that combine territorial and consumption-based emissions, we use the post-peak slope as the indicator of recent territorial emissions trajectory.

We classify administrative units based on the estimated post-peak slope and its statistical significance. Units with a statistically significant positive post-peak slope are classified as Rising, units with a statistically significant negative post-peak slope are classified as Declining, and units with a non-significant post-peak slope are classified as Static. For units whose peak occurs in 2021 or 2022, there are insufficient post-peak observations to estimate a post-peak slope; these units are therefore assigned to the Rising category to reflect that peak emissions occur at the end of the observation window.

5. Data availability

All of the processed datasets are available.[40]

6. Competing interests

The authors declare no competing interests.

7. Acknowledgements

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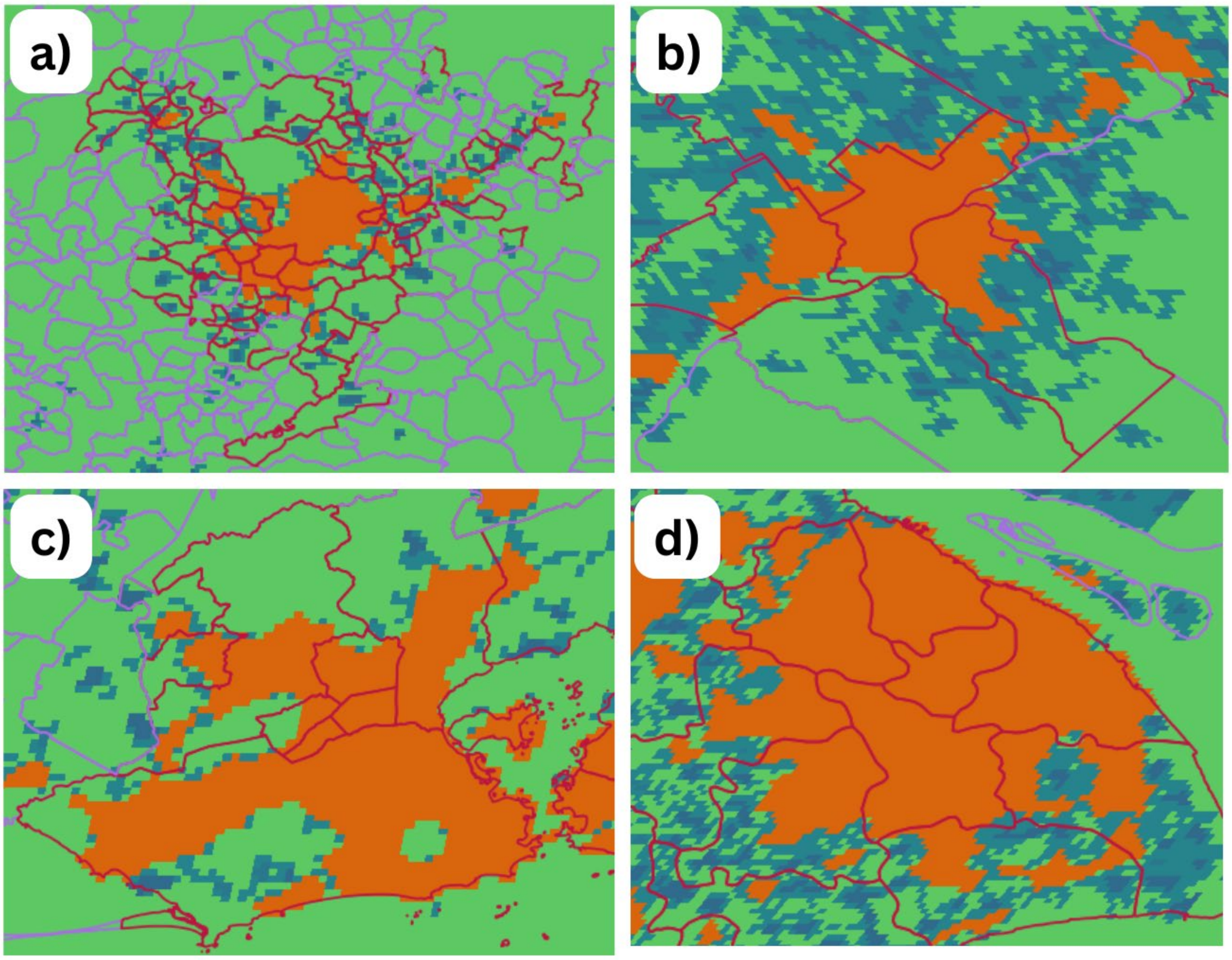
Supplementary Information

Aligning emissions with decisionmaking: estimating urban contributions to global carbon dioxide emissions

This PDF file includes:

- Figures S1 to S10
- Tables S1 to S4

Figure S1. Differences in pixel-based classification or urban areas vs administrative-unit-based classification.



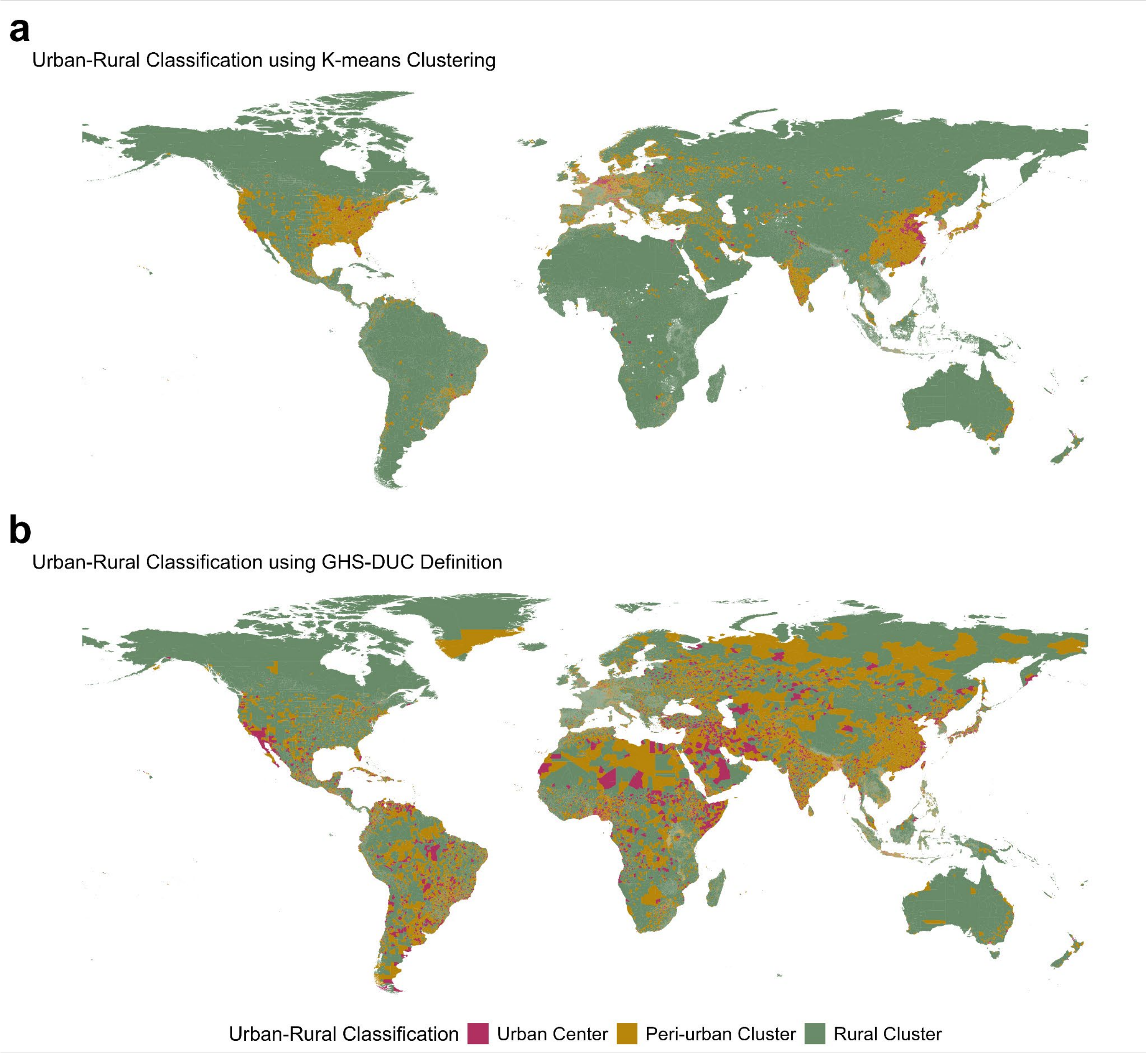
Note: **a,** Madrid, Spain; **b,** Philadelphia, United States; **c,** Rio de Janeiro, Brazil; **d,** Shanghai, China. Background pixels identify the urban, peri-urban, and rural classification defined by the Global Human Settlement Layer-based Degree of Urbanisation (GHS-DUC) (Orange = Urban, Blue = Peri-urban, and Green = Rural). Background boundary lines represent the classification based on GADM administrative areas (Red = Urban, Purple = Peri-urban).

Figure S2 compares our administrative-unit urban–rural typology (panel a) with the Global Human Settlement Degree of Urbanisation classification implemented on GADM administrative units in the EU JRC Stage II analysis (panel b). The underlying Degree of Urbanisation framework was originally developed as a pixel-based settlement typology derived from GHSL population grids, using population density and total population thresholds together with contiguity rules; the Stage II implementation operationalizes this framework at the level of administrative units by applying it to GADM boundaries.

Under our classification, urban centres, peri-urban clusters, and rural clusters account for 33%, 27%, and 40% of the global population and 53%, 31%, and 16% of global GDP, respectively. Under GHS-DUC, the corresponding shares are 43%, 44%, and 13% of the population and 56%, 33%, and 10% of GDP (Table S2). Relative to our typology, GHS-DUC assigns a larger fraction of administrative units and a larger share of population to the urban and peri-urban categories.

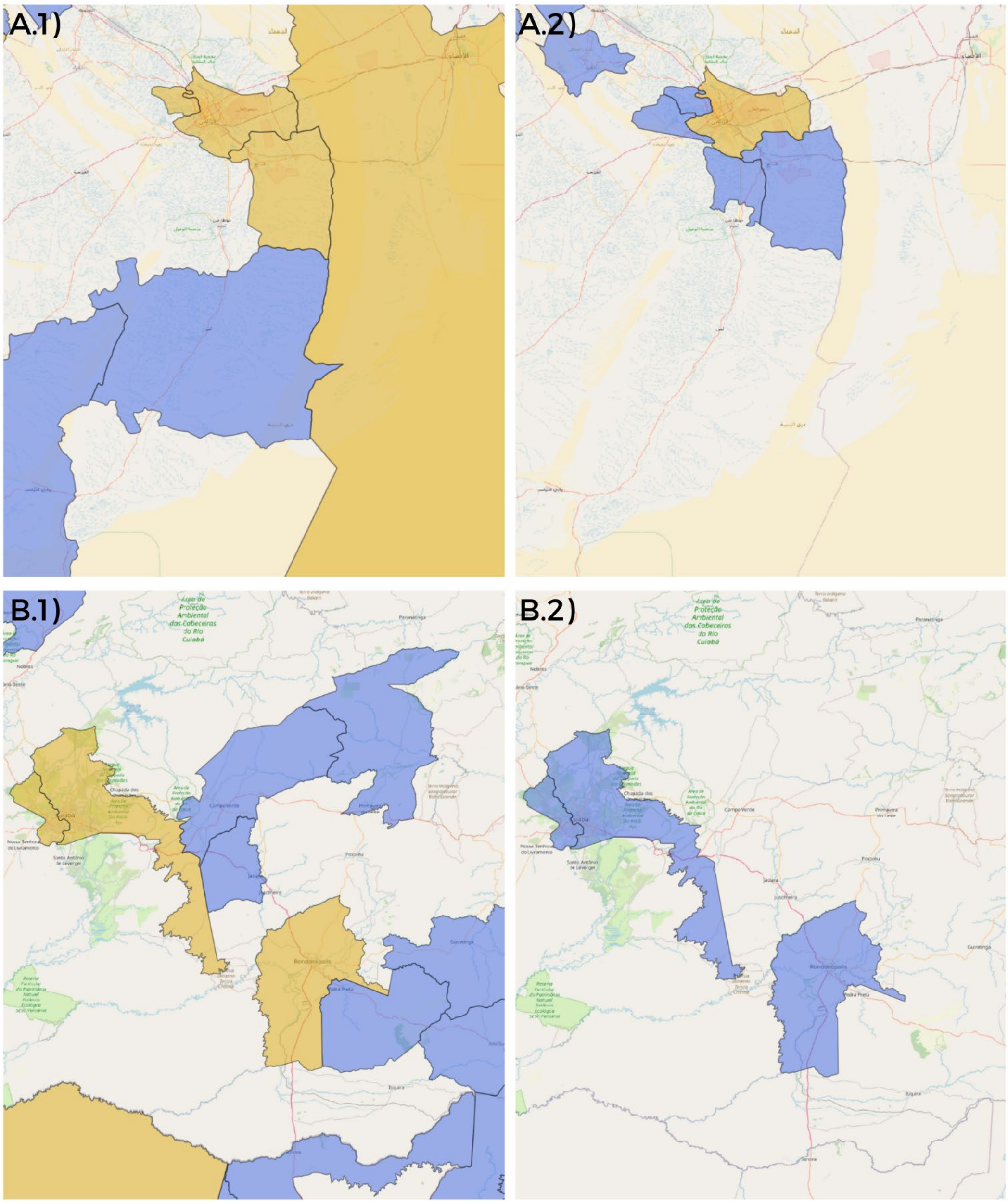
Differences are most pronounced for large, sparsely populated administrative units, notably across parts of Africa, South America, and the Middle East, where a small dense core can shift the classification of an otherwise heterogeneous jurisdiction under population/density-driven rules. At the unit level, approximately 20% of units classified by GHS-DUC as urban centres are classified as peri-urban under our approach, and approximately 70% of units classified by GHS-DUC as peri-urban are classified as rural under our approach (Table S2). These divergences reflect the broader feature set used in our clustering approach, which incorporates indicators of economic activity and long-run built-up change in addition to contemporary population and built-up measures, thereby differentiating established urban centres from rapidly urbanising peri-urban zones in contexts where administrative units are large or where peri-urban expansion is rapid (Figure S3). These classification differences provide context for the sensitivity of estimated “urban contributions” in the emissions results when alternative typologies are applied.

Figure S2. Urban-Rural Classification using (a) K-means clustering method in this study, and (b) Global Human Settlement Degree of Urbanization Classification (GHS-DUC).



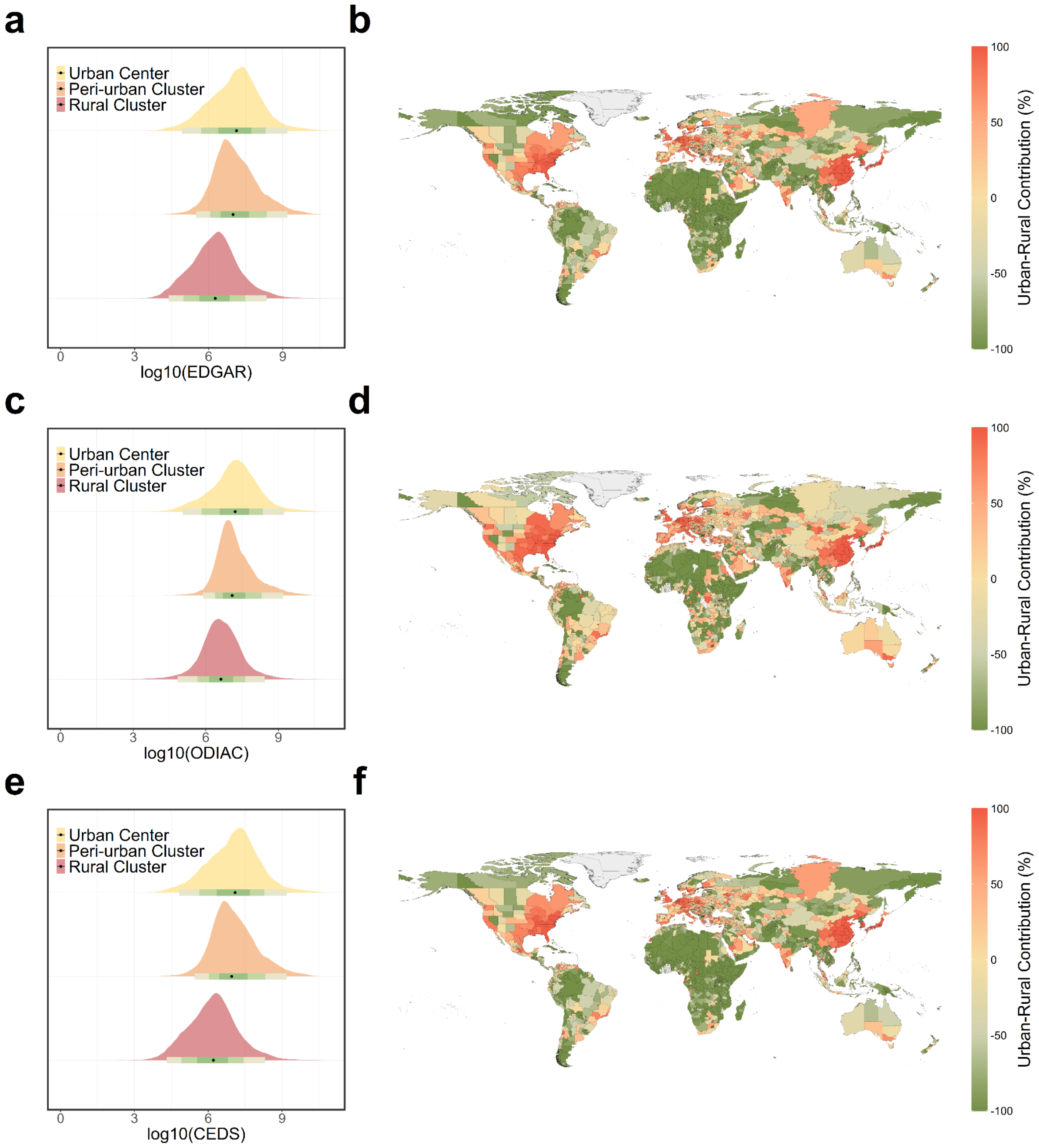
Note: The original GHS-DUC product is a pixel-based settlement typology derived from GHSL population grids, using population density and total population thresholds together with rules on pixel contiguity. In the EU JRC Stage II implementation, Schiavina et al. (2023) applied the Degree of Urbanisation methodology to GADM administrative units, producing an administrative-unit classification. We use this Stage II GADM-based product as the benchmark comparator in this study.

Figure S3. Comparison of Different Urban-Rural Classifications: Global Human Settlement Degree of Urbanization (GHS-DUC) vs. K-Means Clustering Approach (This Study).



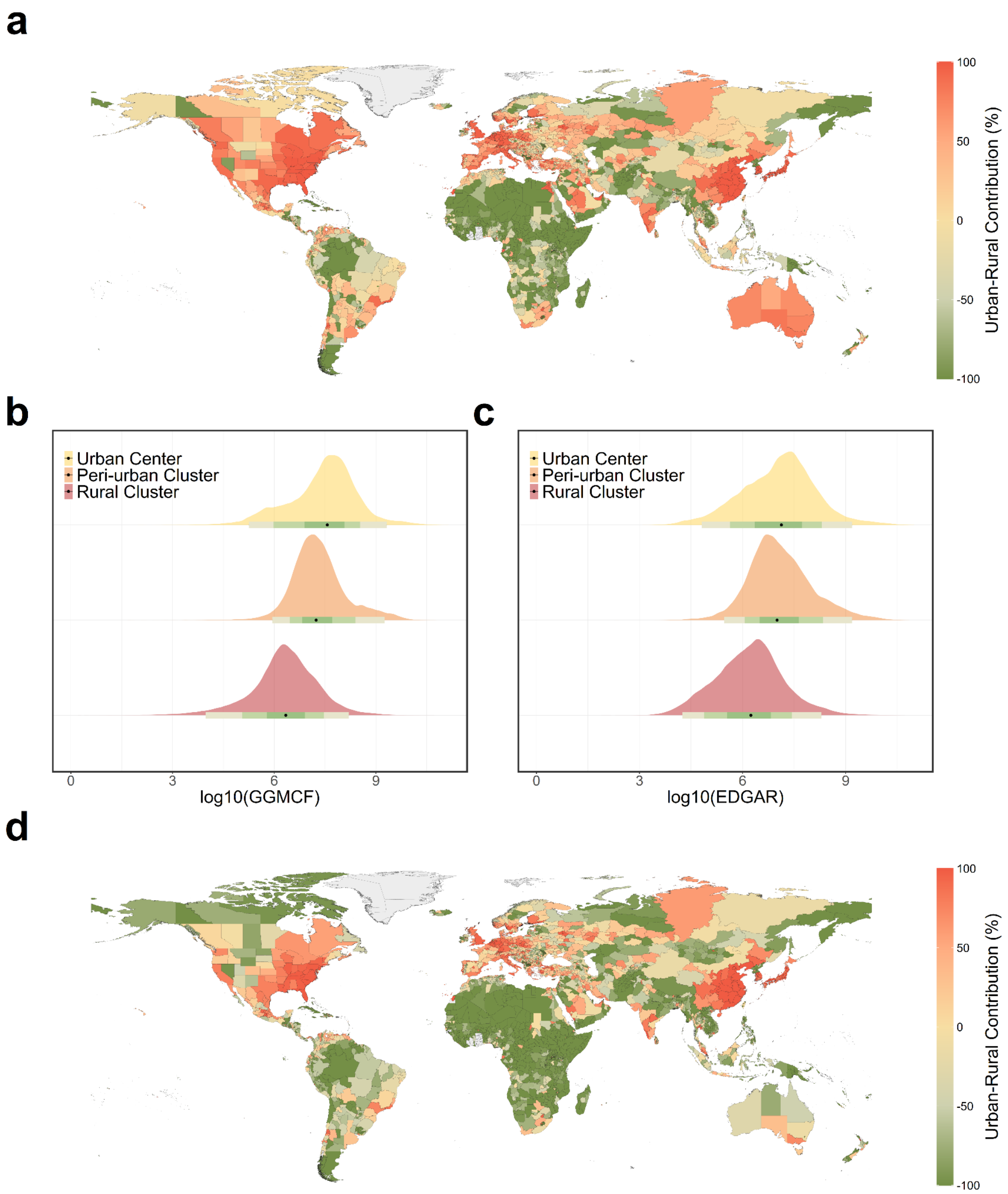
Note: Highlights of classification results from GHS-DUC (A.1, B.1) and our k-means clustering results (A.2, B.2) for sections of Saudi Arabia (A.1, A.2) and Brazil (B.1, B.2). Entities in Blue are classified as the Peri-urban Cluster and entities in Yellow are classified as Urban Center according to the respective sources, The GHS-DUC results incorporate many administrative units under its 'Urban Center' classification with significant low population density due to its use of population proportion as the main variable for urban-rural classification. By contrast, our clustering method incorporates various human settlement variables covering population distribution, economic activities, and physical built-up environment which classifies large and low populated areas as 'Rural Cluster'.

Figure S4. Territorial emissions by urban-rural classifications for each individual dataset



Note: **a**, distribution of EDGAR territorial emissions across urban centers, peri-urban clusters, and rural clusters; **b**, absolute difference between urban and rural contributions to EDGAR territorial emissions; **c**, distribution of ODIAC territorial emissions across urban centers, peri-urban clusters, and rural clusters; **d**, absolute difference between urban and rural contributions to ODIAC territorial emissions; **e**, distribution of CEDS territorial emissions across urban centers, peri-urban clusters, and rural clusters; **f**, absolute difference between urban and rural contributions to CEDS territorial emissions; Urban contribution measures the share of global emissions emitted from urban centers and peri-urban clusters. Rural contribution measures the share of global emissions emitted from rural clusters. Urban-Rural Contribution refers to the gap between the two. Emission values are presented on a logarithmic scale (log10).

Figure S5. Consumption-based emissions by urban-rural classifications.



Note: **a**, absolute difference between urban and rural contributions to consumption-based emissions; **b**, distribution of consumption-based emissions across urban centers, peri-urban clusters, and rural clusters; **c**, distribution of EDGAR territorial emissions across urban centers, peri-urban clusters, and rural clusters; **d**, absolute difference between urban and rural contributions to territorial emissions. Urban contribution measures the share of global emissions emitted from urban centers and peri-urban clusters. Rural contribution measures the share of global emissions emitted from rural clusters. Urban-Rural Contribution refers to the gap between the two. Emission values are presented on a logarithmic scale (log10).

Figure S6. The Emission Gap Between Per Capita Consumption-based Emissions and Territorial Emissions.

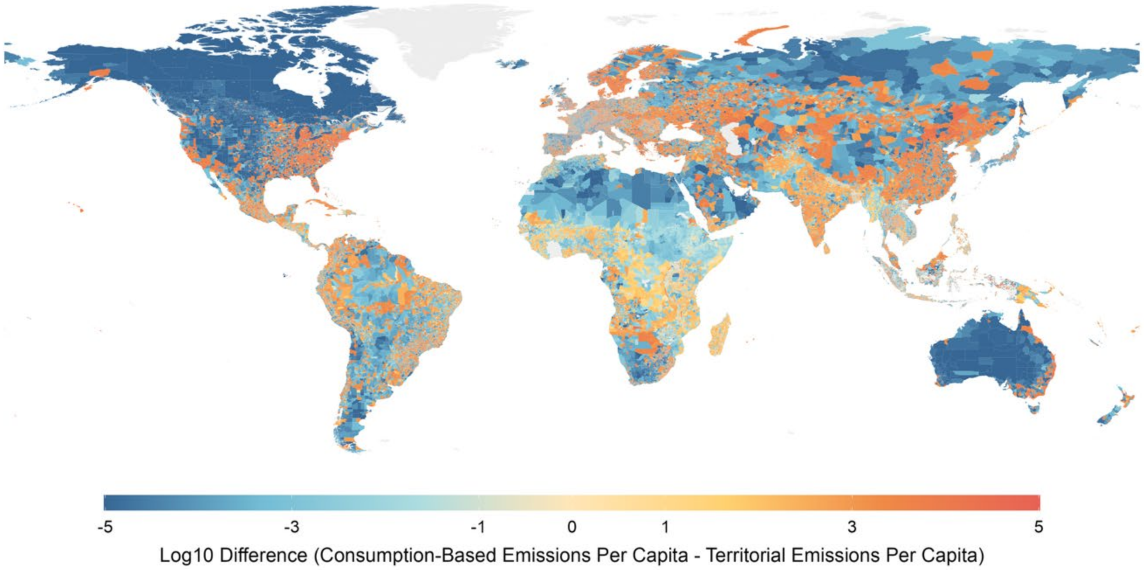


Figure S7. Comparison of National and Subnational Urban Emission Gaps.

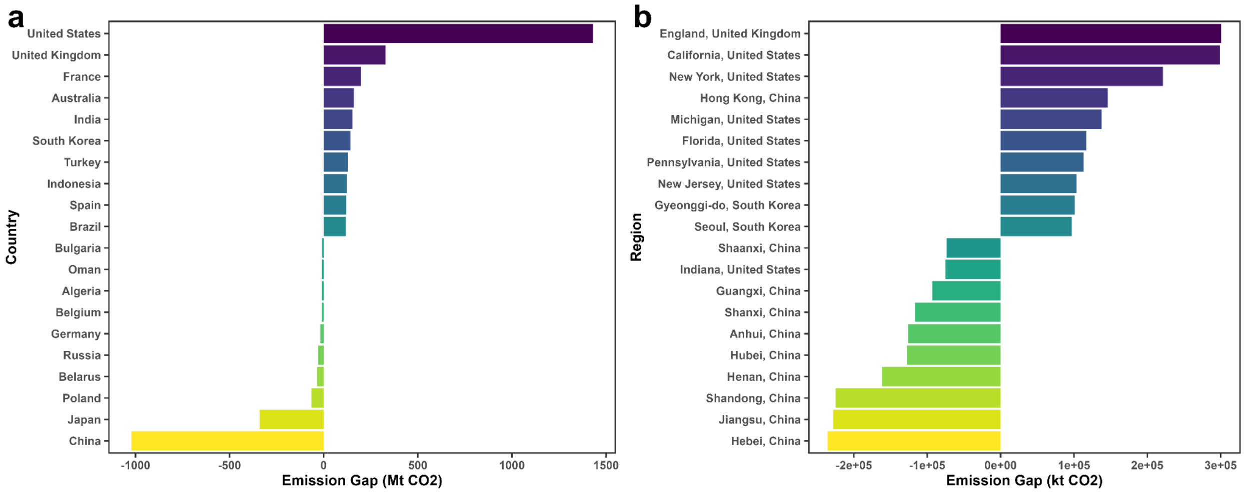


Figure S8. CO_2-Equivalent Emissions by Sector for Global Urban Areas.

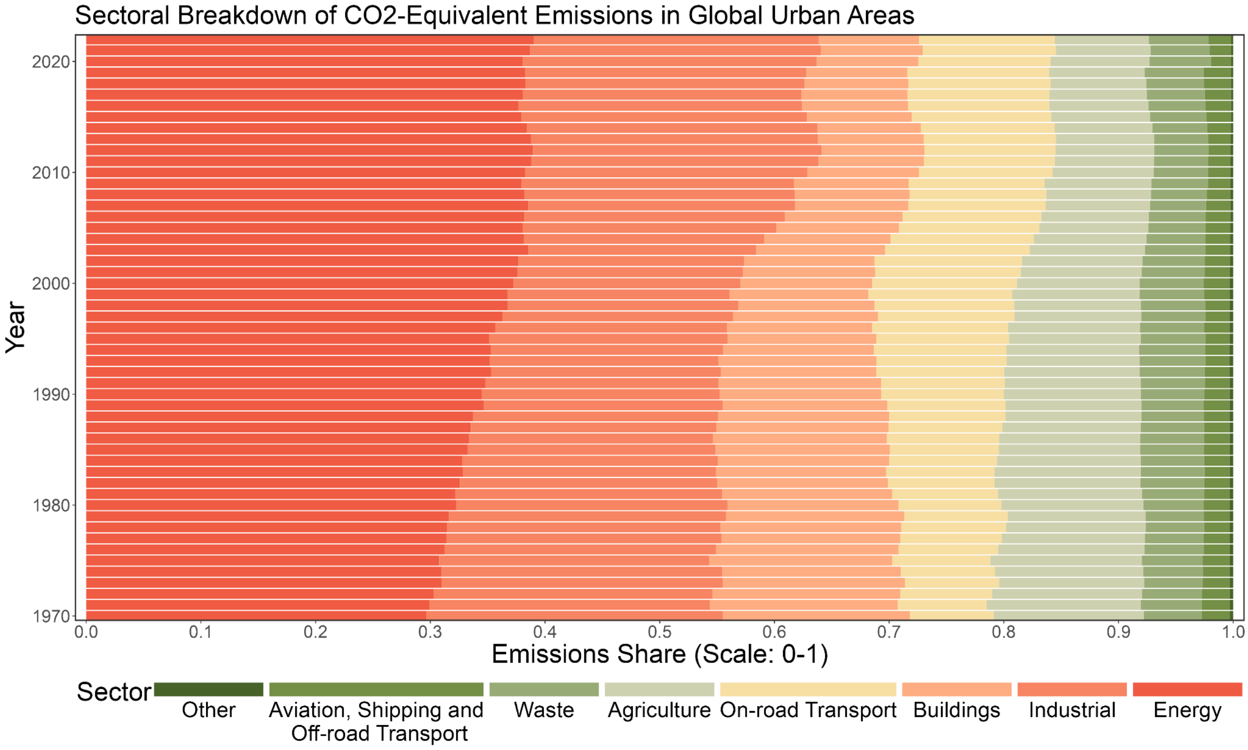
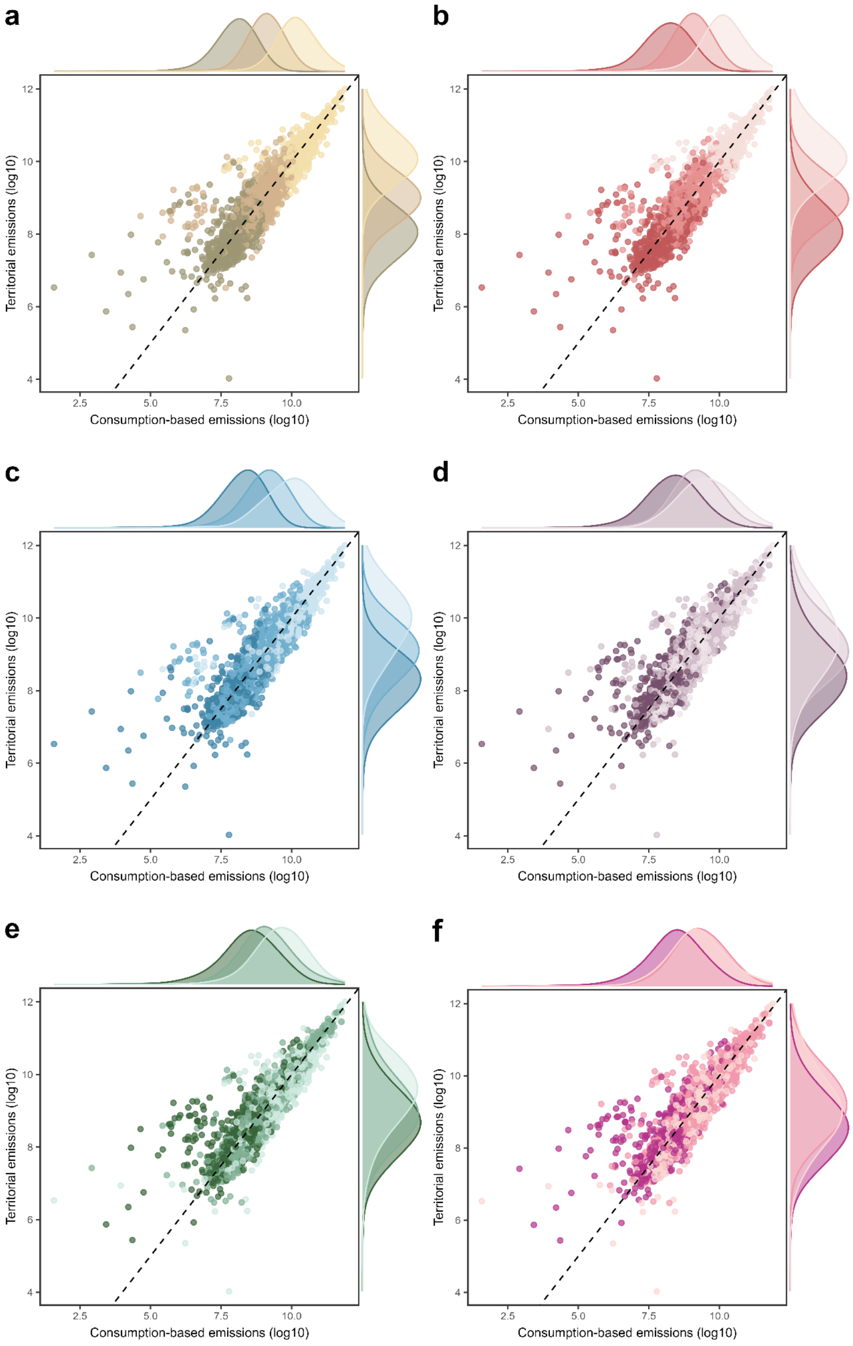


Figure S9. Distribution of Consumption-Based and Territorial Emissions Across Different Groups.



Note: Each panel displays the scatter plot and kernel density distribution of consumption-based and territorial emissions across different tertile groups: (a) GDP, (b) electricity consumption, (c) population, (d) population density, (e) percentage of built-up surfaces relative to land area , and (f) built-up surface change. Each variable is divided into tertiles, with lighter colors representing the highest tertile and darker colors representing the lowest tercile. Emission values are presented on a logarithmic scale (log10).

Figure S10. Radar plot for urban center, peri-urban cluster, and rural cluster classifications.

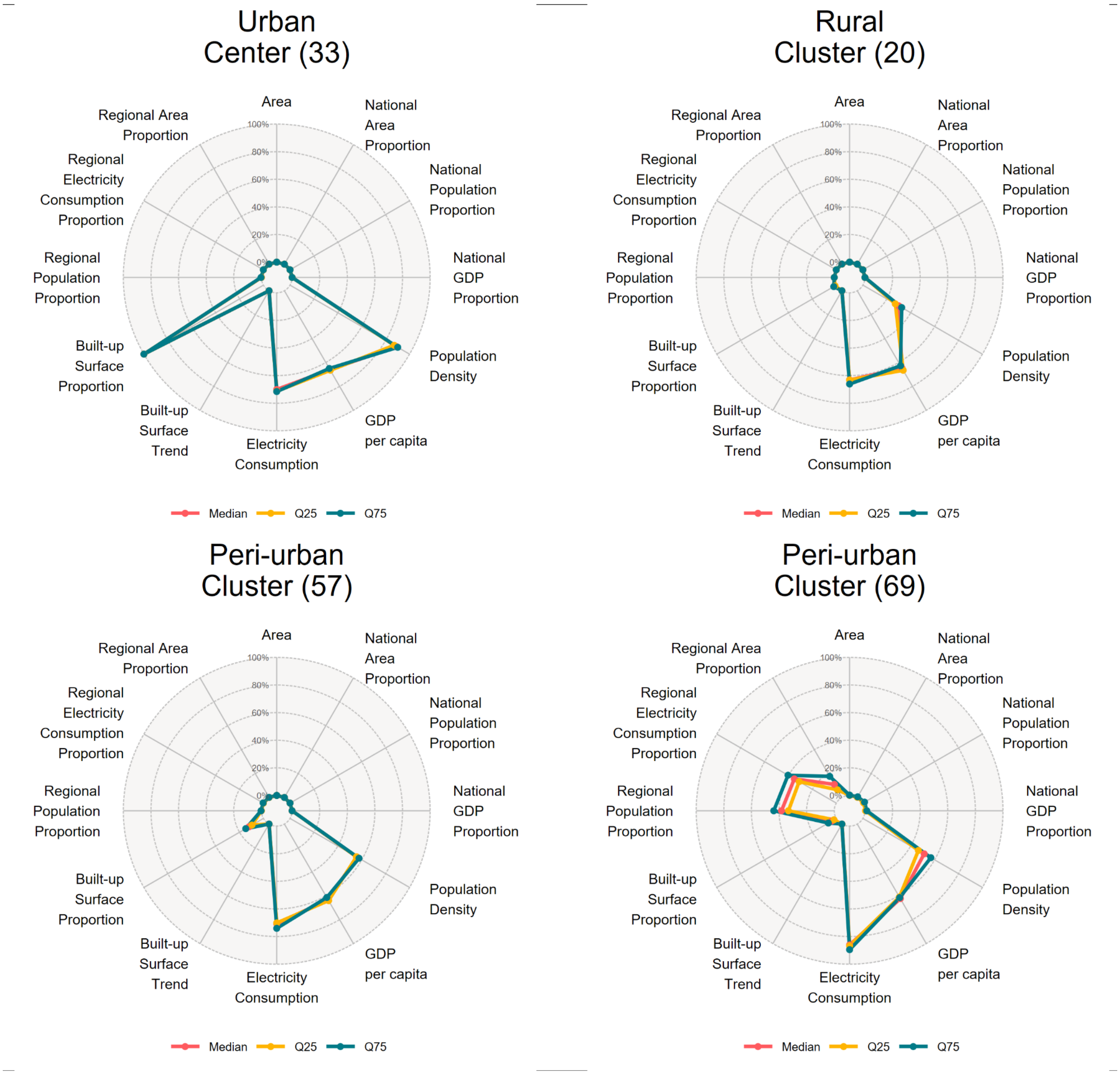


Table S1. Sector Aggregation.

Sector Category	EDGAR Sector Code	Description
Aviation, Shipping and Off-road Transport	TNR_Aviation_SPS	Aviation supersonic
Aviation, Shipping and Off-road Transport	TNR_Aviation_CRS	Aviation cruise
Aviation, Shipping and Off-road Transport	TNR_Aviation_CDS	Aviation Climbing & Descent
Aviation, Shipping and Off-road Transport	TNR_Aviation_LTO	Aviation landing & takeoff
Aviation, Shipping and Off-road Transport	TNR_Other	Railways, pipelines, off-road transport
Aviation, Shipping and Off-road Transport	TNR_Ship	Shipping
On-road Transport	TRO	Road transportation
Agriculture	AWB	Agricultural waste burning
Agriculture	N2O	Indirect N2O emissions from agriculture
Agriculture	MNM	Manure management
Agriculture	ENF	Enteric fermentation
Agriculture	AGS	Agricultural soils
Industrial	NEU	Non energy use of fuels
Industrial	NFE	Non-ferrous metals production
Industrial	PRU_SOL	Solvents and products use
Industrial	IRO	Iron and steel production
Industrial	CHE	Chemical processes
Industrial	NMM	Non-metallic minerals production
Industrial	IND	Combustion for manufacturing
Waste	WWT	Waste water handling
Waste	SWD_INC	Solid waste incineration
Waste	SWD_LDF	Solid waste landfills
Energy	PRO_FFF	Fuel Exploitation
Energy	REF_TRF	Oil refineries & Transformation industry
Energy	ENE	Power industry
Buildings	RCO	Energy for buildings
Other	IDE	Indirect emissions from NOx and NH3

Table S2. Urban-Rural Contribution to Global Territorial and Consumption-based Emissions

	Urban-rural classification in this study			Urban-rural classification based on GHS-DUC		
	Urban Center	Peri-urban Cluster	Rural Cluster	Urban Center	Peri-urban Cluster	Rural Cluster
Population share (%)	33.1	27.4	39.5	42.6	44.1	13.3
GDP share (%)	52.9	31.2	15.9	56.2	33.4	10.4
Contribution to Global Consumption-based Emissions (%) (GGMCF in 2015)	43.8	38.3	17.8	47.1	39.5	13.3
Contribution to Global Territorial Emissions (%) (EDGAR in 2015)	30.5	42.9	26.6	33.6	44.5	21.9
Contribution to Global Territorial Emissions (%) (ODIAC in 2015)	37.2	39.4	23.4	41.8	40	18.2
Contribution to Global Territorial Emissions (%) (CEDS in 2015)	29.9	43.3	26.8	33.6	44.6	21.9

Table S3. Data Sources.

Dataset	Data Source	Spatial/Temporal Resolution	Temporal Coverage
Emissions Database for Global Atmospheric Research (EDGARv8.0)	https://edgar.jrc.ec.europa.eu/dataset_ghg80#p2	0.1 degree/Annual	1970-2022
Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC)	https://db.cger.nies.go.jp/dataset/ODIAC/DL_odiac2024.html	0.05 degree/ Monthly	2000-2023
Community Earth Atmospheric Data System (CEDS)	https://metagrid.esgf-west.org/search	0.1 degree/ Monthly	1980-2023
Global Gridded Model of Carbon Footprints (GGMCF)	https://citycarbonfootprints.info/[1]	250m/Annual	2015
Gross Domestic Product (GDP)	https://zenodo.org/records/13943886	30 arc-sec/every 5 years	1990–2022
Global Human Settlement (GHS) Population	https://human-settlement.emergency.copernicus.eu/ghs_pop2023.php	100m/every 5 years	1975-2030
Global Human Settlement (GHS) Built-up surface	https://human-settlement.emergency.copernicus.eu/ghs_buS2023.php	100m/every 5 years	1975-2030
Electricity Consumption	https://doi.org/10.6084/m9.figshare.17004523.v1	1km/Annual	1992–2019
Global Administrative	https://gadm.org/data.html	Administrative levels 0-5	-

Areas (GADM v4.1)

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[1] In the dataset, certain urban areas are assigned 0 consumption-based emissions despite having resident populations. To address this inconsistency, we impute these cases as missing (N/A) as a quality control measure, recognizing that such anomalies likely stem from extraction algorithm errors associated with small or fragmented geometries.

Table S4. Kruskal-Wallis Results for Urban Center (30), Peri-urban (20) and Rural (10) Clusters

Variable	Rural Cluster (Median)	Rural Cluster (IQR)	Peri-urban Cluster (Median)	Peri-urban Cluster (IQR)	Urban Center Cluster (Median)	Urban Center Cluster (IQR)	H-Statistic	Eta_Squared
Built-up Area Proportion	-0.43	0.15	-0.17	0.40	1.61	2.50	179828.12	0.50
Population Density	-0.29	1.29	0.01	0.94	1.51	0.91	112543.69	0.32
Electricity Consumption	0.04	0.62	0.65	0.54	0.60	0.88	77363.17	0.22
GDP per capita	-0.28	1.07	0.82	0.86	0.53	1.20	65550.31	0.18
Built-up area Trend	-0.02	0.00	-0.02	0.00	-0.02	0.00	44861.49	0.13
GDP proportion (National)	-0.07	0.01	-0.06	0.01	-0.05	0.04	42725.83	0.12
Population proportion (National)	-0.07	0.01	-0.07	0.02	-0.06	0.03	34563.61	0.10

Area	-0.07	0.01	-0.07	0.01	-0.07	0.00	28447.14	0.08
Area Proportion (National)	-0.08	0.02	-0.08	0.02	-0.08	0.00	20924.07	0.06
Area Proportion (Region)	-0.16	0.07	-0.17	0.06	-0.17	0.02	18043.86	0.05
Electricity Consumption Proportion (Region)	-0.17	0.04	-0.16	0.08	-0.16	0.08	14773.92	0.04
Population Proportion (Region)	-0.16	0.05	-0.16	0.06	-0.14	0.09	8073.71	0.02