Bridging Territorial and Consumption-Based Emissions for Urban Climate Action Assessment

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Abstract

Urban areas are responsible for the vast majority of global carbon dioxide (CO_2) emissions, yet their full contribution, particularly from consumption-based sources, remains inconsistently measured. To address this problem, we provide an updated and globally consistent estimate of urban contributions to both territorial and consumption-based emissions, finding that urban areas account for 87% of global consumption-based emissions and 78% of territorial emissions, with densely populated urban centers alone responsible for 54% and 43% respectively. We also examine how the composition of urban territorial emissions has evolved from 1970 to 2022, identifying a sharp rise in emissions from the energy sector and relative declines in contributions from industry and buildings. Finally, by comparing territorial and consumption-based emissions across regions, we map the global distribution of carbon leakage and find that 63% of subnational regions consume more emissions than they produce. These findings reveal critical blind spots in current urban climate strategies and highlight the need to integrate consumption-based accounting to fully capture cities' mitigation responsibilities.

Keywords: Urban Carbon Footprint; Urban Emission Inventories; Urban Climate Planning; Carbon Leakage

Introduction

Subnational and non-state actors, particularly cities, play a crucial role in mitigating climate change and reducing greenhouse gas (GHG) emissions (Hsu et al., 2019, 2020a). By 2050, the global urban population is projected to surge to 68%, with the associated expansion of infrastructure, energy consumption, and transportation activities likely to further increase urban CO_2 emissions. As urban areas expand throughout the world (Seto et al., 2011; Van Vliet, 2019) and subnational governments become increasingly central to achieving global climate actions and mitigation targets, it is imperative to have consistent data by which to compare their global CO_2 emissions and assess their emission reduction performance. Despite this imperative, however, data and evidence are still lacking regarding multiple dimensions of cities and urban areas' contributions to global mitigation, including how city climate actions lead to global emissions reductions (Seto et al., 2012). Such quantification is necessary for subnational governments' understanding of how to assess and improve their mitigation efforts.

Further complicating the data availability dimension of subnational climate action assessment is the fact that cities' consumption-based emissions may extend beyond their territorial emissions (Wiedmann et al., 2021). While these direct emissions from production processes within territorial boundaries and corresponding climate commitments have been extensively studied (Fan et al., 2016; Peters, 2008), assessing indirect emissions associated with the consumption of goods and services beyond city boundaries remains considerably more complex. These consumption-based emissions encompass indirect emissions occurring throughout the supply chain, including with the production, transportation, use, and disposal of goods and services (Davis and Caldeira, 2010; Mi et al., 2016; Wiedmann, 2009). Since consumption-based emissions include both direct emissions within a city's boundaries and indirect emissions from its supply chain, accurately accounting for them is essential to fully capturing a city's actual carbon footprint. Previous studies have shown that one quarter of the top 200 cities with highest consumption-based emissions emit more than their territorial emissions (Moran et al., 2018). This difference suggests that CO_2 emissions associated with urban residents' consumption, and by extension, their mitigation responsibilities, may be displaced to other regions -- a well-known problem called "carbon leakage," when companies outsource production to other areas with less stringent environmental regulations and offset global climate mitigation efforts (Böhringer et al., 2017; Wang and Kuusi, 2024).

Thus, quantifying the gap between consumption-based and territorial emissions and optimizing mitigation targets requires robust, granular data—yet much of what is currently available comes from self-reported disclosures. Many subnational governments disclose their CO_2 emissions and set mitigation targets through voluntary reporting initiatives, including the Carbon Disclosure Project (CDP), the Global Covenant of Mayors for Climate & Energy (GCoM). However, the reliability and accuracy of these self-reported emissions remain uncertain due to the lack of standardized methodologies and quality control, particularly concerning consumption-based emissions. Additionally, significant inconsistencies exist in reporting years, accounting boundaries, and methodological approaches, leading to limited data comparability, especially among entities in the Global South (Kuramochi et al., 2020). The absence of traceability and transparency in reported data further complicates cross-dataset comparison, constraining the ability to assess aggregated emissions reductions at a global scale or to identify which practices can be shared or transferred between contexts. These challenges underscore the urgent need for globally standardized data evaluating all urban-relevant emissions scopes to enable consistent comparisons and calibration of urban climate policies.

Advances in high-resolution gridded datasets present new opportunities to bridge gaps in self-reported emissions, facilitating comprehensive monitoring and comparison of territorial and consumption-based CO_2 emissions. Our contributions are threefold: first, we introduce a new approach to delineating the degree of urbanization across Global Administrative Areas (GADM) Levels 1-5 by integrating statistical clustering approaches with various human settlement activity factors. The resulting urban-rural classification is used to facilitate globally consistent and administratively coherent evaluations of the urban contribution to both territorial and consumption-based emissions (see Methods). Second, we evaluate how urban territorial emissions have evolved over time, offering insights into the shifting relative importance of different sectors within urban areas. Third, we systematically quantify the gap between consumption-based and territorial emissions across all subnational administrative divisions to evaluate where jurisdictions might be "leaking" emissions within a territorial boundary to out-of-boundary locations upstream or downstream the value chain. By linking high-resolution gridded emissions inventories with two-dimensional consumption-based and territorial emissions at all subnational administrative levels, we not only provide a consistent dataset for other researchers but also assist policymakers with practical insights into mitigation opportunities potentially overlooked when only considering one scope of emissions.

Results

Quantifying the global urban contribution to territorial and consumption-based emissions

A key step in assessing urban contributions to global emissions is the comprehensive delineation of urban areas; however, the lack of a standardized and consistent definition of "city" has constrained the development of comparable urban emissions inventories (Xu et al., 2025). To address this limitation, we develop an urban-rural classification method based on k-means clustering (Hartigan and Wong, 1979). This approach identifies distinct groups of administrative units along the urban-rural continuum based on variables reflecting human settlement patterns, including the physical built environment, population distribution, and economic activity (See Methods for more detail). 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. Building on this classification, we integrate multiple high-resolution, spatially explicit datasets to systematically quantify subnational territorial emissions (Emissions Database for Global Atmospheric Research or EDGAR) and consumption-based emissions (Global Gridded Model of Carbon Footprints or emissions Global Gridded Model of Carbon Footprints or GGMCF) (see Data sources in Methods for more detail). Together, these datasets allow us to consistently measure the relative contributions of urban and rural areas to global CO_2 emissions.

We find that urban areas globally account for 87% of consumption-based emissions and 79% of territorial emissions, while urban centers contribute 54% and 43%, respectively (see Table S1). These findings not only quantify the urban contribution to global consumption-based emissions but also provide an updated assessment of urban contributions to territorial emissions, revisiting estimates reported a decade ago (Grubler et al., 2012; Kennedy et al., 2009; Satterthwaite, 2008). Our updated urban-rural definition produces estimates of urban center contributions that are slightly higher than those of Global Degree of Urbanization Classification of administrative units delineated by GADM (GHS-DUC) (Schiavina et al., 2023). We use GHS-DUC classification as a benchmark given its endorsement by international agencies like the United Nations and the European Union's Joint Research Commission and broad use as a standardized, globally comparable framework for delineating urban areas (Florio et al., 2023; Yu et al., 2024). Under the GHS-DUC definition, urban areas contribute 87% of global consumption-based emissions and 78% of global territorial emissions, while urban centers contribute 47% and 34%, respectively. Although the overall shares are similar, our approach extends beyond GHS-DUC's focus on population size, density, and built-up area by also incorporating economic activity, land cover, and long-term land use change—especially imperviousness trends over the past four decades. This enables us to better delineate established urban centers and capture fast-growing peri-urban zones in emerging economies such as China and India (see Figures S3–S5).

The spatial distribution of urban and rural contributions to consumption-based emissions, calculated as the relative share within each Administrative Level 1 region (Figure 1a), reveals a clear predominance of urban-driven emissions, with urban areas contributing a larger share than rural areas across most regions in high-income countries, including the United States, Canada, Australia, Saudi Arabia, Japan, and EU member states. On the contrary, low- and lower-middle-income countries have very few regions with high urban contribution; instead, many regions either have similar urban and rural contributions, or have a much higher rural contribution, such as the majority of African regions (e.g., Mali, Ethiopia, or Mozambique), Cambodia, or Iran. Moreover, upper-middle income countries exhibit greater variability in urban and rural contributions. Many of these countries – such as Peru, Chile, Argentina, Brazil, China, and Indonesia – contain regions where consumption-based emissions are primarily driven by urban areas, as well as regions where rural areas are the main contributors. Figure 1d illustrates the spatial distribution of urban and rural contributions to territorial emissions, showing a similar pattern overall but with a less pronounced urban-rural disparities in high-income and middle-income countries.

Sectoral evolution of urban territorial emissions

Using territorial emissions data from the EDGAR dataset and our urban–rural classification method, we analyze the evolution of sectoral CO_2 emissions in urban areas from 1970 to 2022, encompassing total emissions from both urban centers and peri-urban clusters. To facilitate analysis of sectoral emissions, we aggregate the original 27 EDGAR sectors into 7 policy-relevant major categories: Energy, Industrial, Buildings, On-road Transport, Aviation & Shipping and Off-road Transport, Agriculture, and Waste (see Table S2).

Across all urban areas worldwide, the highest emitting sector is Energy, whose share of territorial emissions rose from 34% in 1970 to approximately 45% in 2022, peaking since the early 2000s (Figure 2a). The second-largest contributor is the Industrial sector, which declined slightly from 32% in 1970 to 28% in 2022, with minimal change since around 2009. The Buildings sector ranks third and has seen a steady decline from 20% in 1970 to 10% in 2022. Finally, the fourth contributor is the On-road Transport sector, which increased from 9% in 1970 to 13% in 2022, peaking at around 15% in the early 2000s. Other sectors such as Aviation & Shipping and Off-road Transport, Agriculture, and Waste collectively contribute less than 5%.

While the global sectoral breakdown of urban emissions appears relatively stable, individual countries exhibit more pronounced shifts in certain sectors of their urban emissions patterns (Figure 2b). For example, the share of China's urban territorial emissions from the Energy sector increased from 20% in 1970 to 50% in 2022. Similarly, in India, the Energy sector's emission share rose from 26% to 49% over the same period. Conversely, the United States' Industrial sector has declined from 28% to 13%, while Germany's has fallen less from 28% to 19%.

Mapping emission gaps between consumption-based and territorial emissions across all subnational administrative areas worldwide

To identify subnational regions experiencing carbon leakage, where emissions are effectively outsourced and shifted outside their territorial boundaries, leading to consumption-based emissions exceeding territorial emissions (Grubb et al., 2022), we first calculate the emission gap between consumption-based and territorial emissions for all subnational administrative units globally. The results are presented on a logarithmic scale in Figure 3 and on a per capita basis in Figure S1. Export-oriented and production-intensive regions, such as Hebei Province in China and Chhattisgarh State in India, exhibit substantially higher territorial emissions than consumption-based emissions. In contrast, import-dependent and consumption-driven regions, such as California and New York State in the United States, show higher consumption-based emissions relative to their territorial emissions.

Focusing on urban areas (Figure S2), we find that England (319 million tons or Mt), California (311 Mt), and New York State (221 Mt) exhibit the largest positive urban emission gaps, indicating considerably higher consumption-based emissions compared to territorial emissions. Conversely, the Chinese provinces of Hebei (-233 Mt), Jiangsu (-228 Mt), and Shandong (-225 Mt) display substantial negative gaps, where urban territorial emissions exceed consumption-based emissions.

Identifying urban carbon leakage and patterns across the world

To explore whether the temporal variation in territorial emissions is associated with emission gaps, we calculate territorial emissions for each Administrative Level 1 (i.e., states, provinces, regions) unit using a spline regression for the periods before and after their peak emission year (see Methods). To compare the overall trajectory of each region's territorial CO_2 emissions trend and its emission gaps, we develop a typology based on two dimensions: (1) whether an administrative unit's territorial emissions have increased, decreased, or remained stable between 1970 and 2022; and (2) whether it exhibits carbon leakage, where consumption-based emissions exceed territorial emissions, or carbon haven (Branger and Quirion, 2014), where territorial emissions exceed local consumption, reflecting its role as a receiver of CO_2 emissions leaked from other regions. We find that 63% of all evaluated regions show carbon leakage. Among these, approximately 31% show an increase in territorial emissions, 28% show a decrease, and 4% exhibit stagnation. The other 36% of evaluated regions act as carbon havens, with 16% exhibiting increasing territorial emissions, 18% showing a decline, and 2% remaining stable (Figure 4a).

Focusing on regions exhibiting carbon leakage in relation to levels of economic development, we find that a majority (59%) of regions classified as the Growth & Leak category are located in low- and lower-middle-income countries, primarily concentrated in Africa and the Middle East. Meanwhile, a notable proportion (41%) of these regions are situated in upper-middle- and high-income countries, highlighting the persistent challenges of decarbonization in more developed economies and the need to address their comparatively larger emission gaps (Figure 4b). In contrast, regions categorized as Shrink & Leak are predominantly located in upper-middle- and high-income countries, including Great Britain, France, and Australia, which together account for 72% of this category. The remaining 28% are found in low- and lower-middle-income countries. Despite achieving a steady decline in territorial CO_2 emissions, these regions continue to exhibit substantial emission gaps between consumption-based and territorial emissions, particularly in those with higher levels of economic development, suggesting that climate mitigation responsibilities are transferred through the supply chain (Figure 4c).

Discussion

This study provides the first globally consistent and administratively coherent assessment of subnational territorial and consumption-based emissions using a harmonized urban-rural classification and high-resolution emissions inventories. By integrating the Global Gridded Model of Carbon Footprints (GGMCF) with the Emissions Database for Global Atmospheric Research (EDGAR) and applying a k-means clustering approach to delineate urban centers, peri-urban clusters, and rural clusters on GADM boundaries, we quantify urban contributions to global consumption-based and territorial emissions, analyze sectoral trends over five decades, and spatialize carbon leakage patterns across all subnational entities. Our findings reveal that urban areas account for 87% of global consumption-based emissions and 79% of territorial emissions, with energy and industrial sectors remaining dominant in most cities. Critically, we also find that 63% of regions exhibit carbon leakage, underscoring the reality that cities are not only the primary centers of consumption, but also the main drivers of outsourced emissions. This dual role has profound consequences: it highlights a major blind spot in how urban climate responsibility is assessed, reveals a mismatch between where emissions are generated and where they are consumed, and calls into question the adequacy of territorial-only accounting frameworks for urban climate policy.

Without incorporating consumption-based emissions, cities risk underestimating their true carbon footprints and missing key opportunities for mitigation potential embedded in global supply chains.

The need for greater national support for urban climate action

Our findings highlight the urgent need to center and support urban areas in global mitigation efforts. As we demonstrate, cities and their peri-urban zones are responsible for the vast majority of both territorial and consumption-based emissions, making them indispensable actors in achieving global mitigation goals. However, studies show that despite growing momentum of subnational climate action, cities struggle to achieve progress in implementing their mitigation plans (Hsu et al., 2020b; Song et al., 2024). 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 (Aboagye and Sharifi, 2024). 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 (Gilmore and St.Clair, 2018). Similarly, many of the most ambitious European cities pledging carbon neutrality struggle with even estimating basic financial costs of their decarbonization strategies (Ulpiani et al., 2023). 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 (Robiou du Pont et al., Under Review).

In response to these challenges, 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 (COP28 UAE, 2023).

Correcting emission blindspots for more equitable accounting

Our results also underscore a fundamental limitation of relying solely on territorial emissions accounting: obscuring the full climate impact of jurisdictions that consume more than they produce. This imbalance is especially evident in high-income countries, where territorial emissions may be declining, yet overall carbon footprints remain high due to continued demand for carbon-intensive goods produced elsewhere. Such a disconnect creates a false sense of progress at the global level and poses a serious challenge for climate accountability, as cities and regions may appear to meet emissions reduction targets while effectively outsourcing their emissions through global supply chains.

The well-documented phenomenon of carbon leakage -- the relocation of emissions-intensive production to jurisdictions with weaker environmental regulations or lower mitigation capacity (Aichele and Felbermayr, 2015). As globalization reshapes where emissions occur, manufacturing and energy-intensive sectors have increasingly shifted to lower-income regions, especially in the Global South. For instance, our sectoral analysis shows clear decoupling trends in developed countries: industrial emissions have declined in places like the U.S. and Germany, while rising sharply in countries such as China and India. Meanwhile, a majority (59%) of regions we classify as Growth & Leak are located in low- and lower-middle-income countries, primarily in Africa and the Middle East. In contrast, 72% of regions we classify as Shrink & Leak are in upper-middle- and high-income countries like the United Kingdom, France, and Australia. In these cases, growing territorial emissions are often linked to increasing GDP and industrial development -- suggesting that the burdens of mitigation are being transferred to countries still in the early stages of economic growth (Jakob et al., 2014; Liddle, 2018). 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 (Millward-Hopkins and Oswald, 2021). 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.

Limitations

While our study advances a consistent framework and methodology to evaluate subnational contributions to global territorial and consumption-based CO_2 emissions, several limitations remain. First, 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 (Yang et al., 2018) and may substantially alter the sectoral composition of emissions (see Figure S3). 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 (Jiang et al., 2024; Malley et al., 2023). Second, the consumption-based emissions data used in this study, derived from the Global Gridded Model of Carbon Footprints (GGMCF), is only available for a single reference year, limiting our ability to assess temporal dynamics or track the evolution of carbon leakage over time. Expanding the temporal coverage of consumption-based datasets would significantly enhance the capacity to monitor global mitigation progress and evaluate the effectiveness of climate policies at subnational scales.

Conclusion

As the global community seeks to close the gap between climate ambition and implementation, this study offers a timely and comprehensive framework to assess the full carbon footprint of subnational entities. By integrating territorial and consumption-based emissions through a harmonized urban–rural classification and high-resolution datasets, we reveal the dominant role of cities in both direct and outsourced emissions and highlight the pervasive patterns of carbon leakage that challenge conventional accounting frameworks. Our findings emphasize the urgent need to center cities in global mitigation strategies, not only by acknowledging their emission profiles but also by supporting them with the financial, regulatory, and institutional tools required to implement needed climate actions.

Methods

Data sources

We integrate multiple high-resolution, spatially explicit datasets to quantify subnational territorial and consumption-based emissions. Territorial CO_2 emissions are sourced from the Emissions Database for Global Atmospheric Research (EDGAR v8.0), which provides annual data at a 0.1° resolution from 1970 to 2022. Consumption-based emissions are derived from the Global Gridded Model of Carbon Footprints (GGMCF), offering data at a 250-meter resolution for the reference year 2015. 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. To characterize the degree of urbanization, we incorporate additional geospatial datasets, including gridded GDP (1990–2022, 30 arc-seconds), GHS Population data (1975–2030, 100-meter resolution), gridded electricity consumption (1992–2019, 1-kilometer resolution), and the GAIA dataset on impervious surface change (1985–2018, 30-meter resolution). 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.

Urban clustering

A major challenge in global urban studies lies in the diverse and inconsistent definitions of 'city,' which complicates a globally harmonized classification. Although pixel-level classifications, such as the Degree of Urbanization (Dijkstra et al., 2021), have been widely adopted in fields including public health (Southerland et al., 2022) and environmental studies (Schug et al., 2023), their applicability for policy implementation remains limited. Since most policy actions are administered through delineated administrative units with established accountability structures, effective urban-rural classifications for climate mitigation tracking and related policy applications should be developed at the administrative unit level rather than at the pixel level.

To address this limitation, we develop a new urban-rural classification using k-means clustering to categorize subnational administrative units across levels 1-5 of GADM Version 4.1. The methodology integrates key variables related to human settlement activities spanning physical built environment, population distribution, and economic activities (see Figure S4). These include population size, population density, GDP, electricity consumption, land area, imperviousness (and its long-term changes), along with each administrative unit's relative contribution to national totals.

The scree plot method determines the optimal cluster number by identifying the inflection point (elbow) where within-cluster variance reduction diminishes. Using k-means clustering, we classify all administrative units into 30 subclusters based on human settlement activity similarity. These subclusters are subsequently aggregated into three primary categories: Urban Center, Peri-urban Cluster, and Rural Cluster (see Figure S5).

Finally, we conduct a sensitivity check comparing our urban-rural classification with the Global Degree of Urbanization (GHS-DUC) classification, both applied to all subnational administrative units from GADM version 4.1 (Schiavina et al., 2023) (see Figure S6). Under our classification, urban centers, peri-urban clusters, and rural clusters account for 40%, 32%, and 28% of the global population and 57%, 31%, and 12% of global GDP, respectively. In contrast, the GHS-DUC classification assigns 43%, 44%, and 13% of the population and 56%, 33%, and 10% of GDP to these categories (see Table S1). Compared to our results, the GHS-DUC approach shows an overestimation of urban areas and exhibits misclassification. For example, at least 30% of administrative units classified by GHS-DUC as urban centers are actually part of the peri-urban cluster, while at least 60% of the units classified in the peri-urban cluster by GHS-DUC are in the rural cluster under our classification. This is particularly evident in sparsely populated, large administrative units across Africa, South America, and the Middle East. To the contrary, our results achieve greater accuracy capturing well established cities in Europe and North America, as well as rapidly urbanizing regions in China and India by considering both current economic activity and long-term land-use changes (see Figures S6-7).

Trend estimation

Using the logarithm of CO_2 territorial emissions, yearly time steps, and a spline model, we estimate piecewise linear trends across two segments of the time series: before and after the peak in territorial emissions over the period 1970-2022. For the joint analysis with consumption-based emissions, we focus on the post-peak period. Administrative units exhibiting a statistically significant positive trend in the post-peak period are classified as “Growth”, while those with a statistically significant negative trend are classified as “Shrink”. Administrative units with no statistically significant trend are categorized as “Static”. A special case is made for administrative units whose peak emissions occur in 2021 or 2022, for which trend estimation is not feasible; these are classified as “Growth” due to the recency of their peak.

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Figures

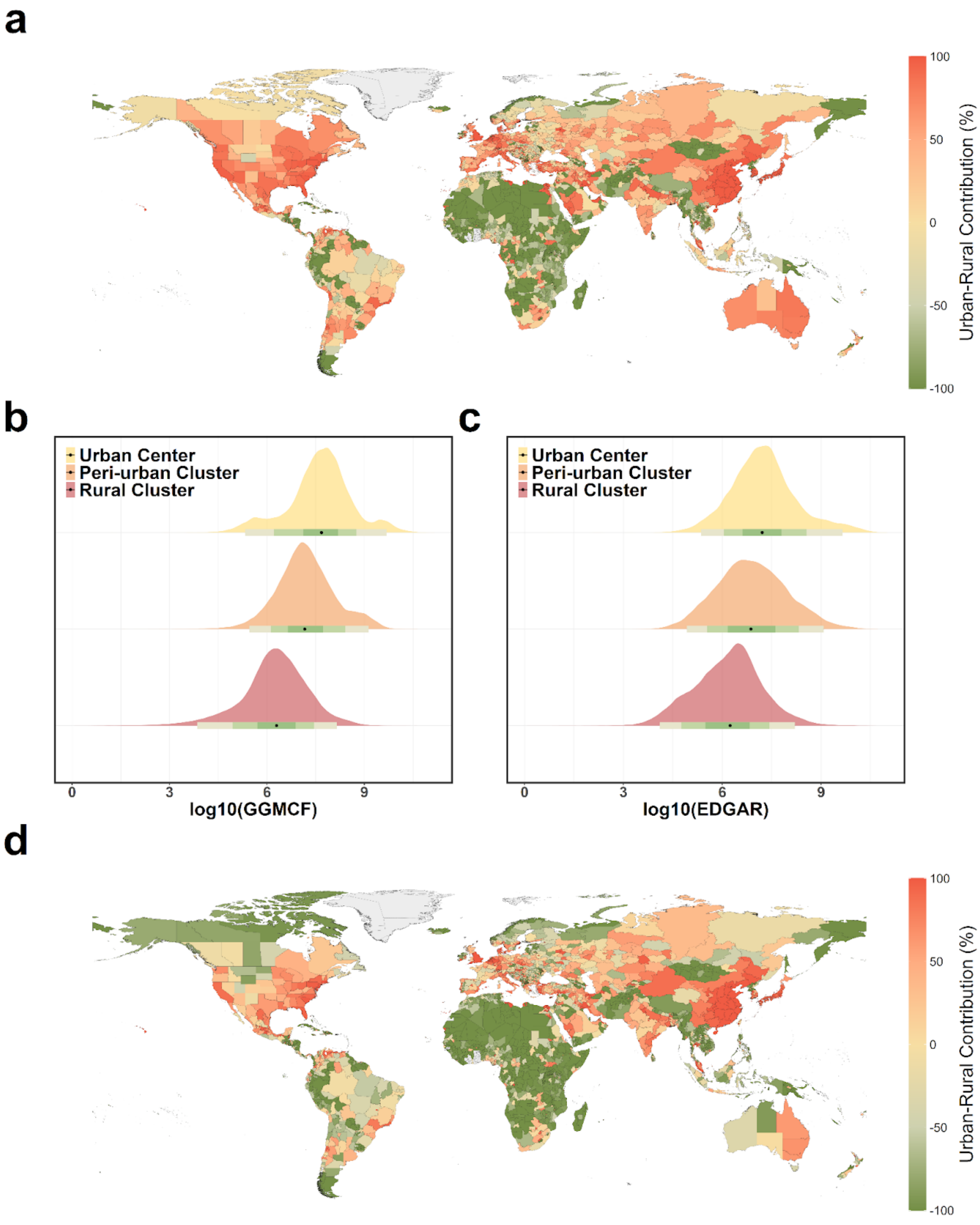

Figure 1. Consumption-based and territorial emissions by urban-rural classifications.

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 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. Emission values are presented on a logarithmic scale (log10).

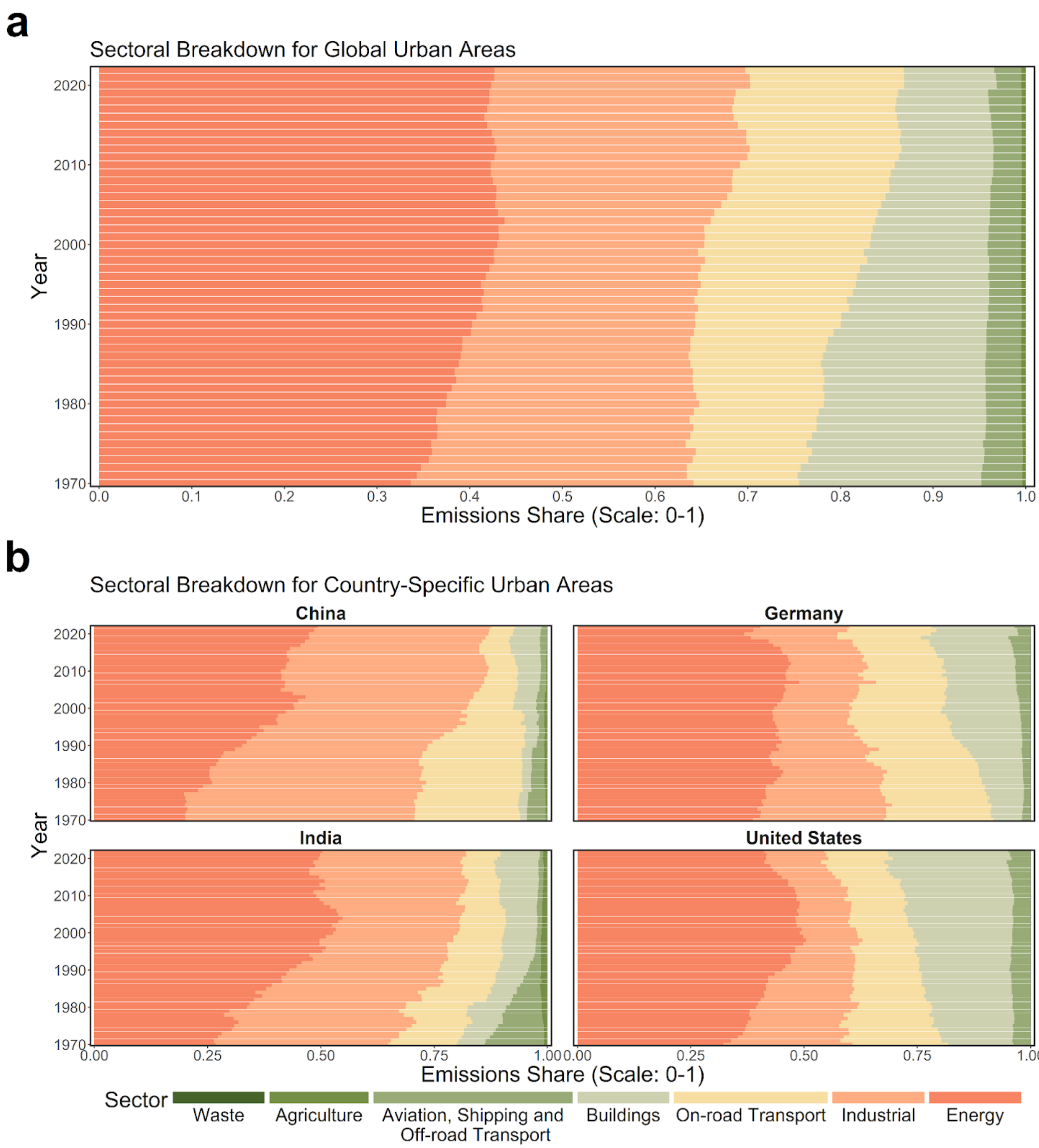

Figure 2. Sectoral breakdown of urban CO_2 emissions worldwide and in major countries.

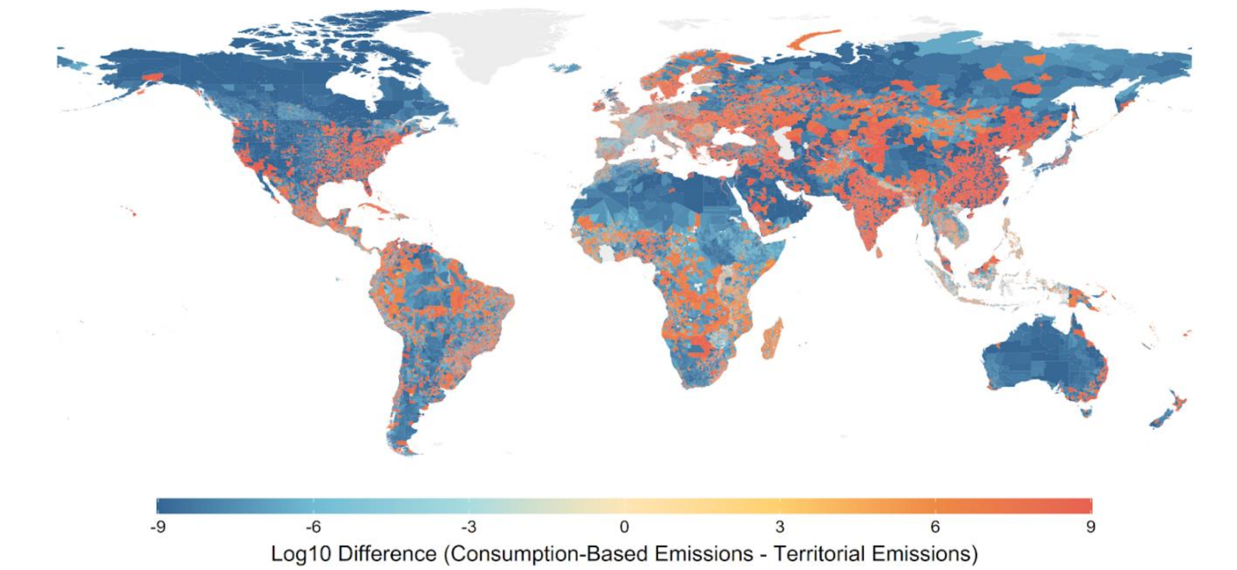

Figure 3. Emission gaps between consumption-based and territorial emissions across all subnational administrative areas worldwide.

Note: The emission gap is calculated by consumption-based emissions minus territorial emissions. Regions in red indicate carbon leakage, where consumption-based emissions exceed territorial emissions, while regions in blue represent carbon haven, 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.

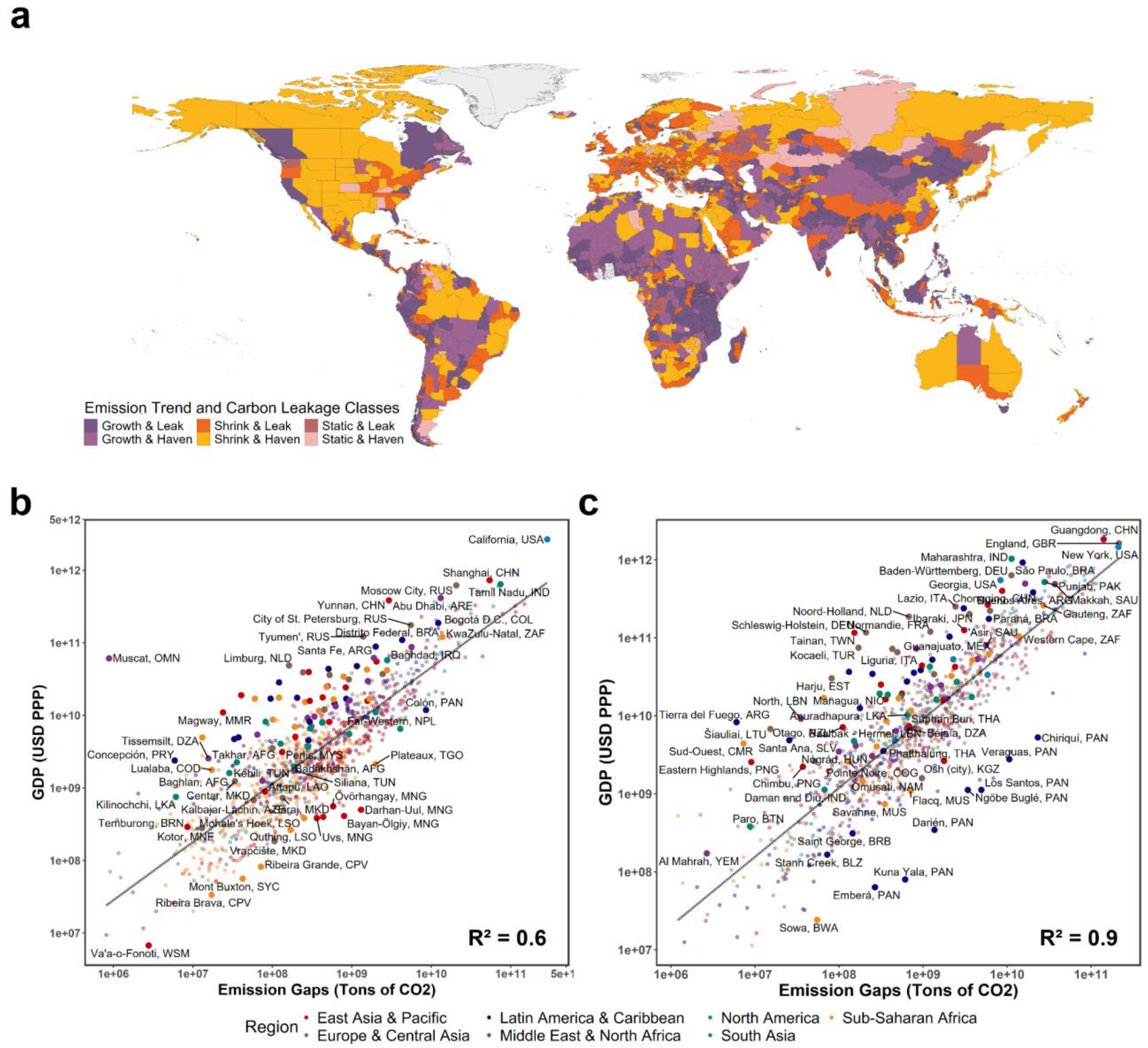

Figure 4. Patterns of territorial emission trajectories and urban carbon leakage.

Note: Panel (a) illustrates the trajectories of territorial emissions alongside the emission gaps between consumption-based and territorial emissions. The categories Growth, Shrink, and Static denote increasing, decreasing, and stable trends in territorial emissions from 1970 to 2022, respectively. The labels Leak and Haven indicate whether a region's consumption-based emissions exceed territorial emissions (Leak), or territorial emissions exceed consumption-based emissions (Haven). Panel (b) shows the relationship between emission gaps and economic development levels for regions in the Growth & Leak category. Panel (c) shows the relationship between emission gaps and economic development levels for regions in the Shrink & Leak category.

Supplementary Information

Bridging Territorial and Consumption-Based Emissions for Urban Climate Action Assessment

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This PDF file includes:

Figures S1 to S7

Tables S1 to S3

Figure S1. The Emission Gap Between Per Capita Consumption-based Emissions and Territorial Emissions.

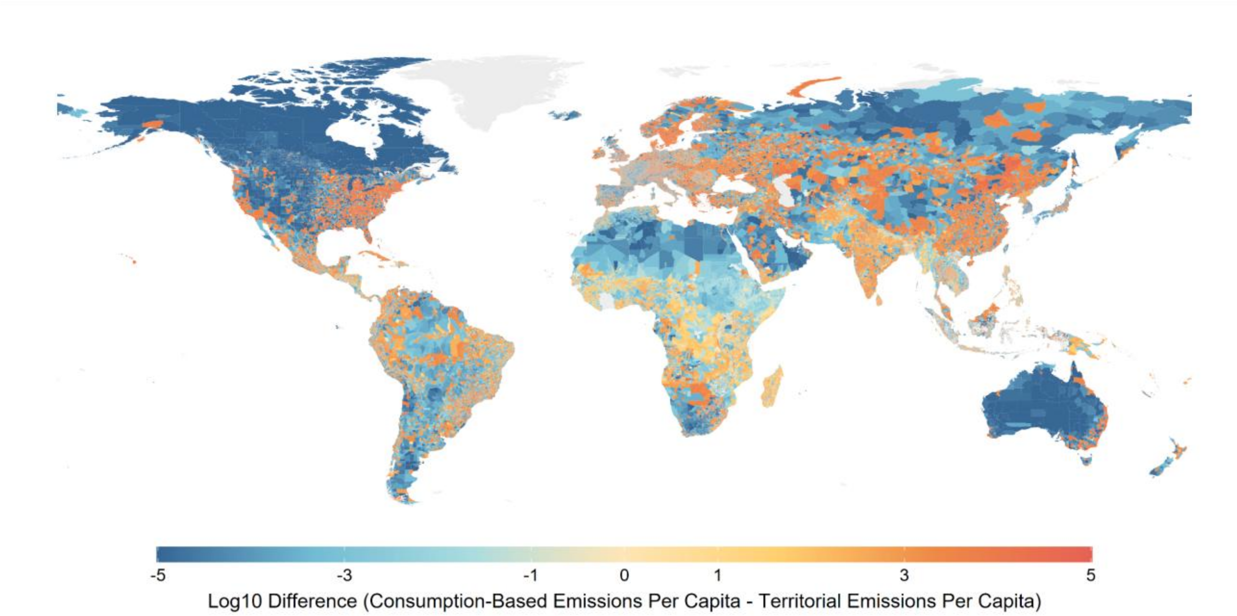


Figure S2. Comparison of National and Subnational Urban Emission Gaps.

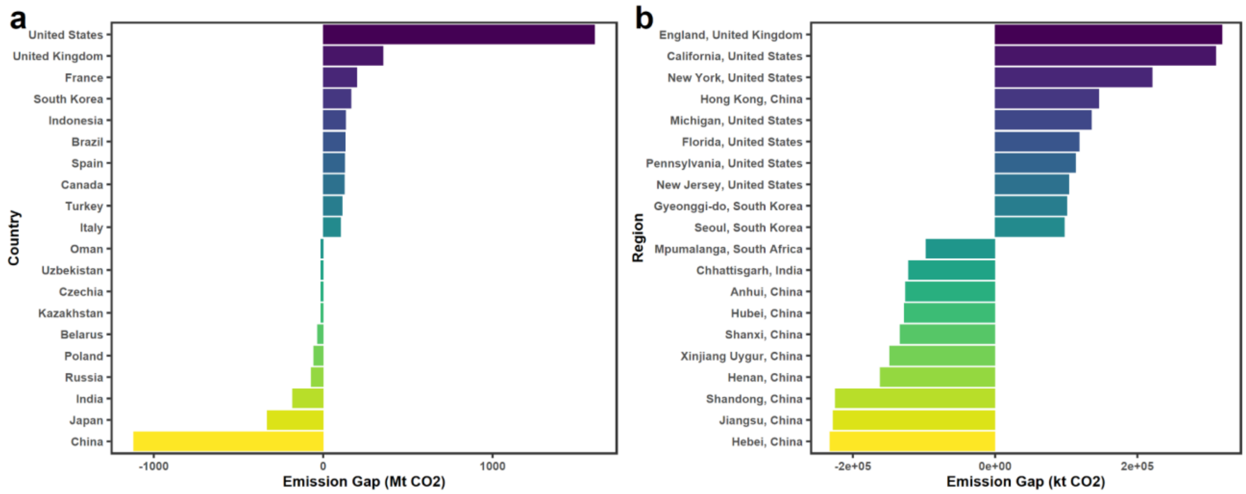


Figure S3. CO_2-Equivalent Emissions by Sector for Global Urban Areas.

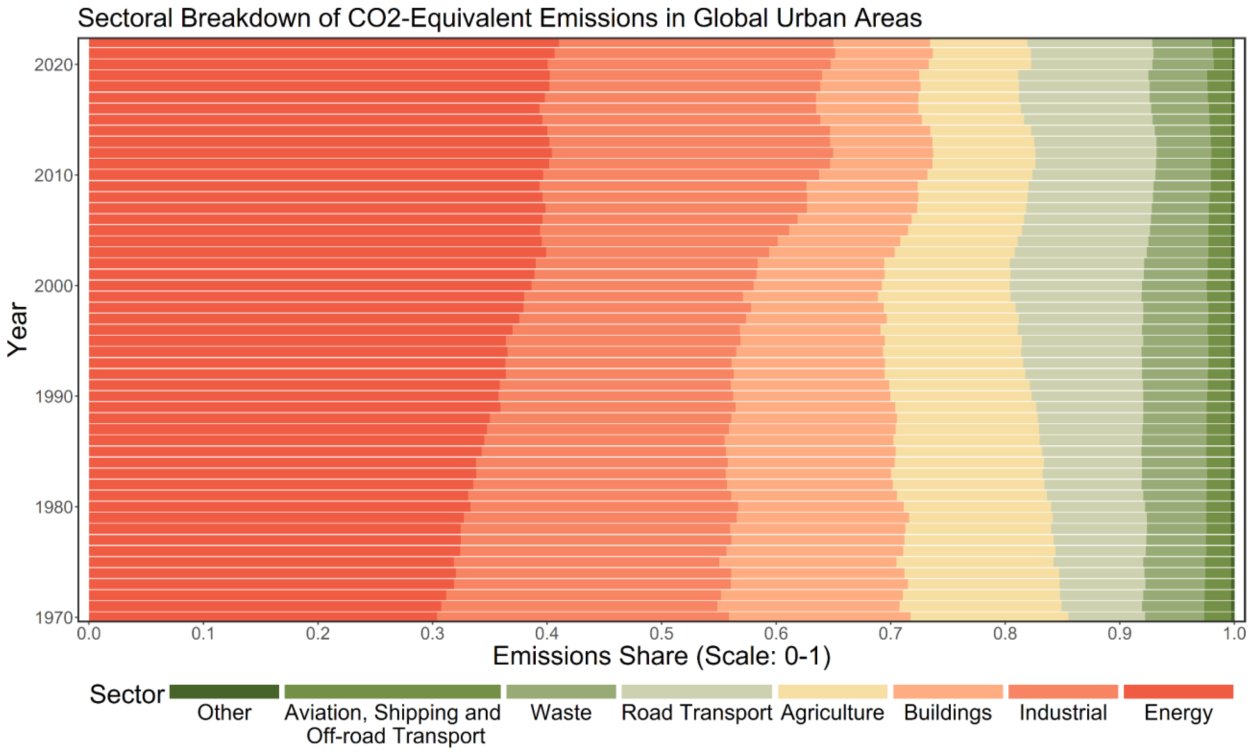
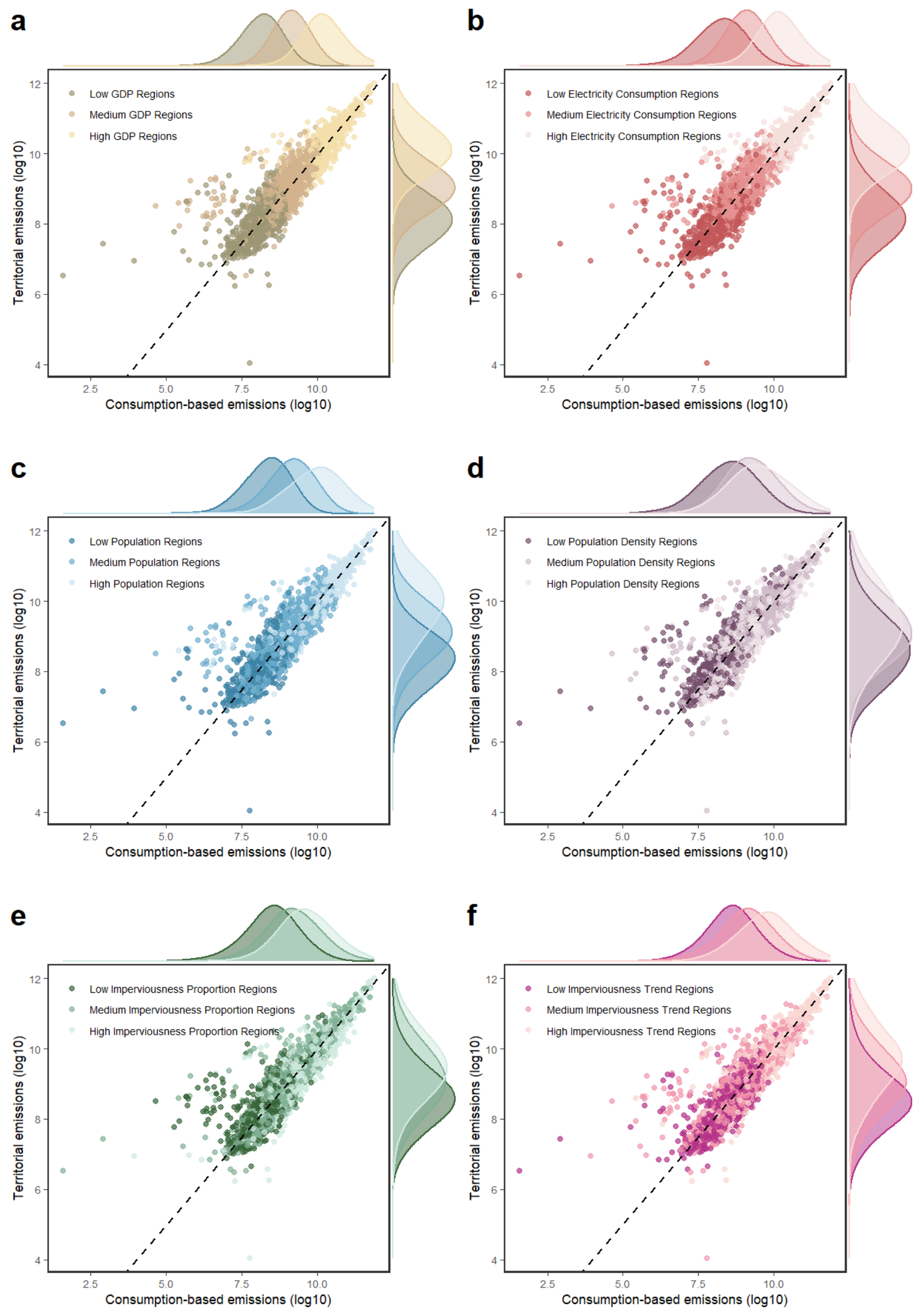


Figure S4. Distribution of Consumption-Based and Territorial Emissions Across Different Groups.



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 imperviousness, and (f) imperviousness 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 S5. Radar plot for urban center, peri-urban cluster, and rural cluster classifications.

Figure S6. Urban-Rural Classification using (a) K-means clustering method in this study, and (b) Global Human Settlement Degree of Urbanization Classification (GHS-DUC).

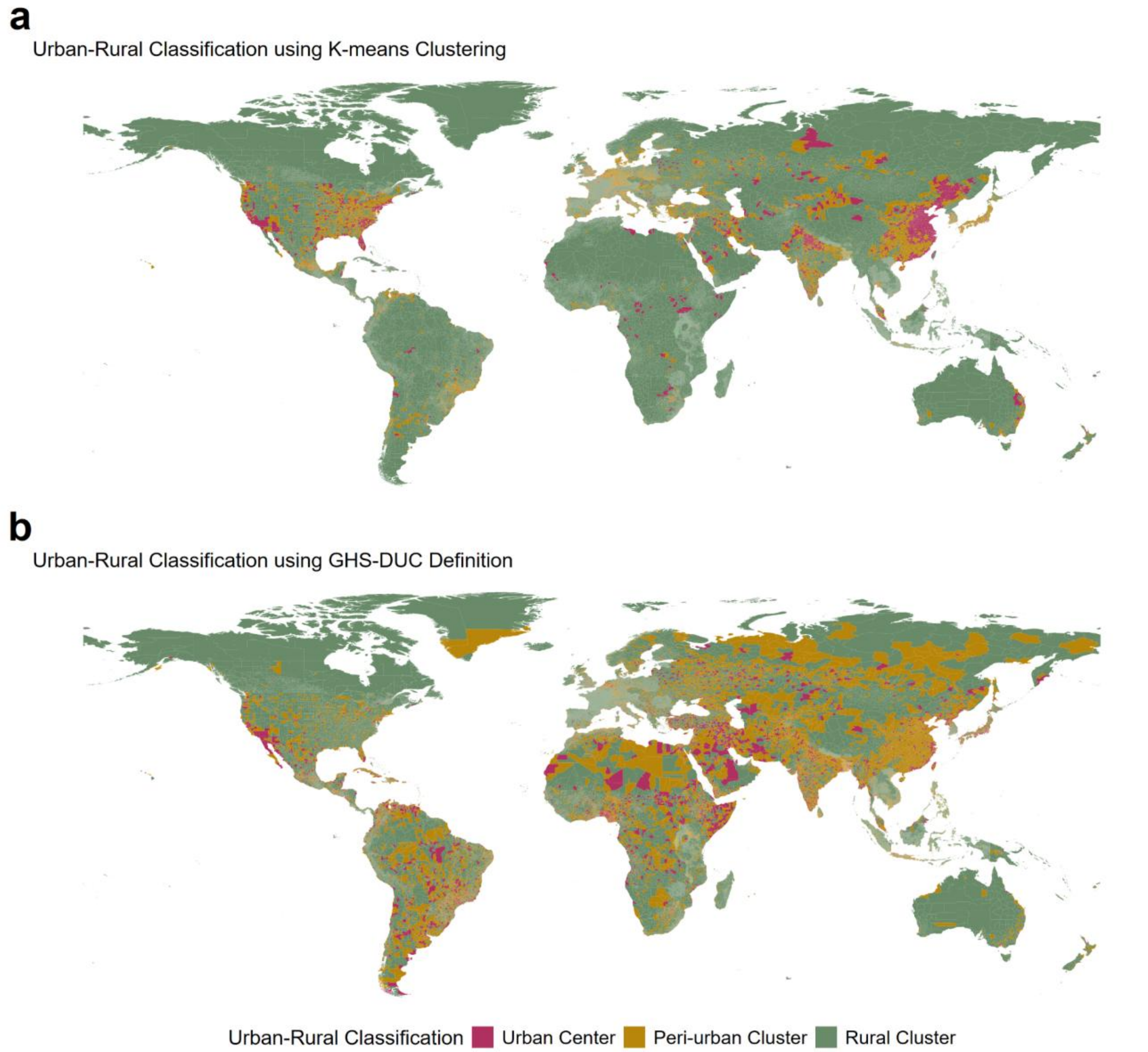
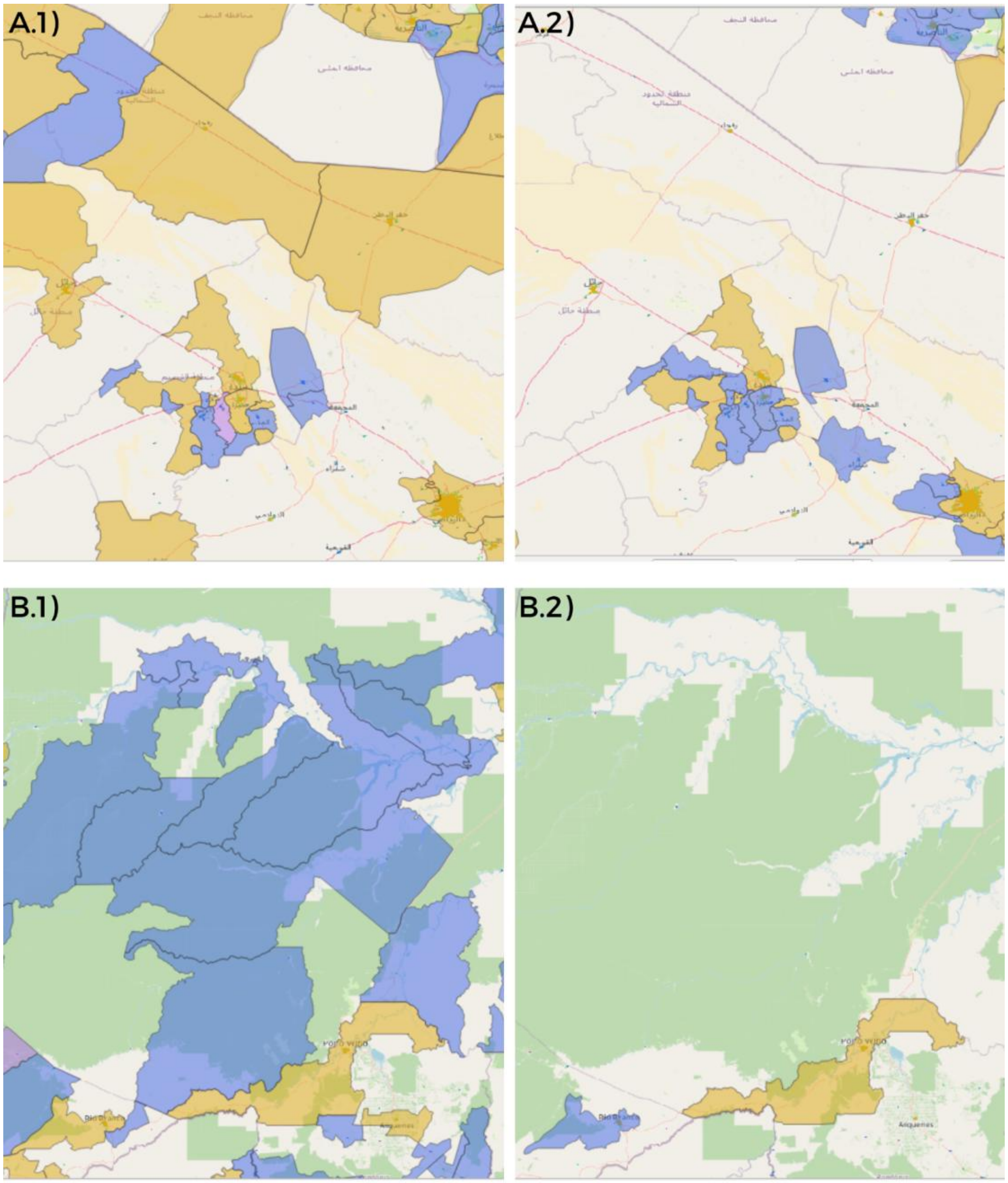


Figure S7. Comparison of Different Urban-Rural Classifications: Global Human Settlement Degree of Urbanization (GHS-DUC) vs. K-Means Clustering Approach (This Study).



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'.

Table S1. 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 (%)	40	32	28	43	44	13
GDP share (%)	57	31	12	56	33	10
Contribution to Global Consumption-based Emissions (%)	54	33	13	47	40	13
Contribution to Global Territorial Emissions (%)	43	36	21	34	44	22

Table S2. 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 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
Global Gridded Model of Carbon Footprints (GGMCF)	https://citycarbonfootprints.info/	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
FROM-GLC Year of Change to Impervious Surface (GAIA)	https://developers.google.com/earth-engine/datasets/catalog/Tsinghua_FROM-GLC_GAIA_v10	30m/Annual	1985-2018
Electricity Consumption	https://doi.org/10.6084/m9.figshare.17004523.v1	1km/Annual	1992–2019
Global Administrative Areas (GADM v4.1)	https://gadm.org/data.html	Administrative levels 0-5	-