Supplementary Information for

The urban share and regional composition of global greenhouse gas emissions

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Text S1. Urban Boundaries

Three globally available urban boundaries are used in this study. The first boundary is the Global Urban Boundaries (GUB) dataset (Li et al., 2020). The second is the Global City and Town Boundaries (GCTB) dataset (Bai et al., 2025). We combine the GCTB "city" and "town" designation in this polygon dataset for the total urban set of polygons. The third polygon boundary dataset is the Functional Urban Areas (FUA) dataset (Moreno-Monroy et al., 2021). The FUA and GUB are combined to create a fourth boundary which we refer to here as the "FUGUB" boundary. It represents two conditions: 1) where a GUB boundary is partly or wholly contained within a FUA boundary the portion contained is fully eliminated from the GUB dataset; 2) GUB delineations that are partly or wholly outside of a FUA urban boundary are retained (Figure S1).

We explored two additional boundaries for this study though neither is used to report the urban share. The Global Administrative Areas (GADM) version 4.1 represents first the world's administrative boundaries at a range of levels (https://gadm.org/index.html). The finest spatial detail that remains globally comprehensive is the GADM level 2. This boundary delineates entities such as districts, provinces and in the case of the United States, counties. Visual inspection of examples of the GADM level 2 boundaries suggests that these are not consistent with what is broadly considered urban and incorporates large portions of rural land surface. Hence, the GADM is not used in the current study.

The urban centre polygon set associated with the Global Human Settlement Urban Centre Database (GHS-UCDB) represents another alternative urban boundary definition (Melchiorri et al., 2024). However, in this case the polygons are restricted to urban "core" or "downtown" areas which exclude suburban or peri-urban areas (Figure S2).

We similarly do not use "pixel-based" definitions of urban areas such as represented by the 1 km^2 Global Human Settlement - Settlement Model (GHS-SMOD) (Schiavina et al., 2023). The use of such pixel-based urban designations requires building the ML model around pixel emissions prediction. Attempts to do so were severely hampered by challenges of computational capacity and data volume. The limited tests that were performed resulted in large prediction errors. Hence, the choice is to only develop the GHG prediction model around the larger and more data-coherent urban polygons.

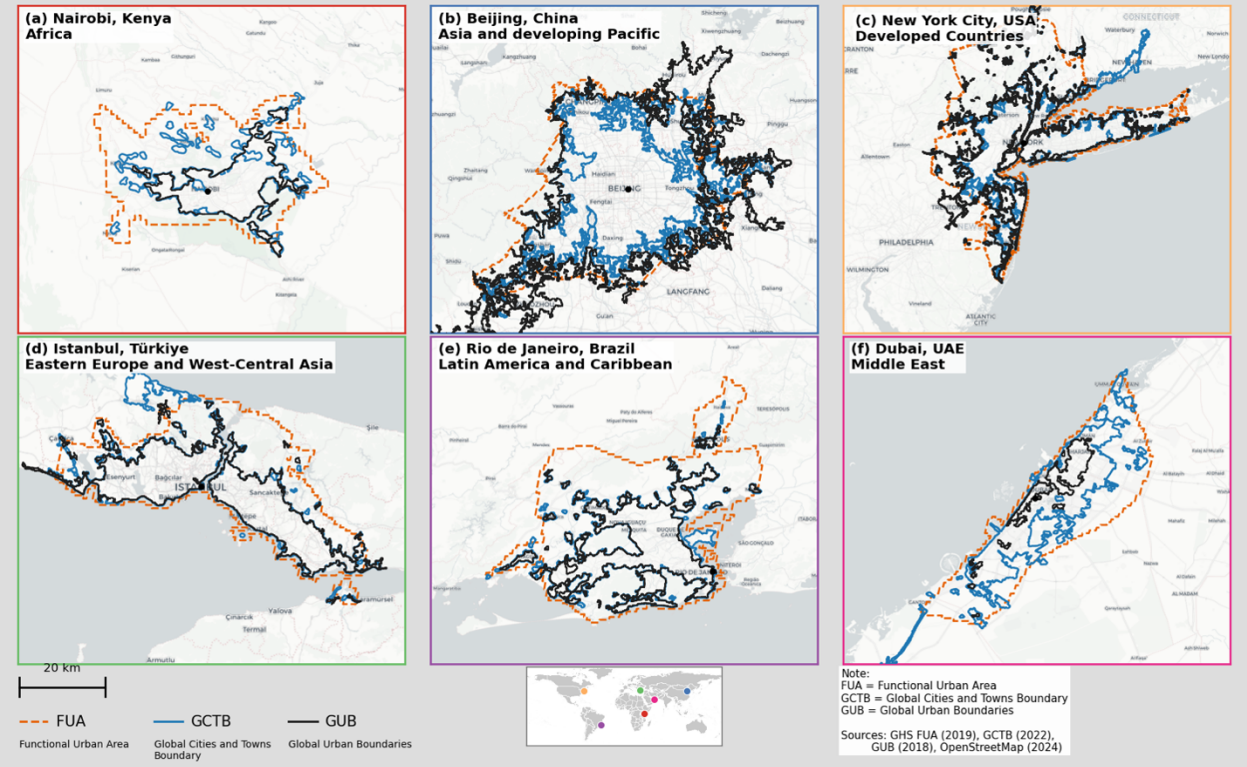

Figure S1. *Example urban boundary outlines in each of the six IPCC regions. Included here are the GUB, FUA, and GCTB boundaries. The hybrid boundary, FUGUB, uses the FUA outline where the GUB is fully contained within the FUA, but adds GUB entities when they partly or are wholly outside of a FUA boundary.*

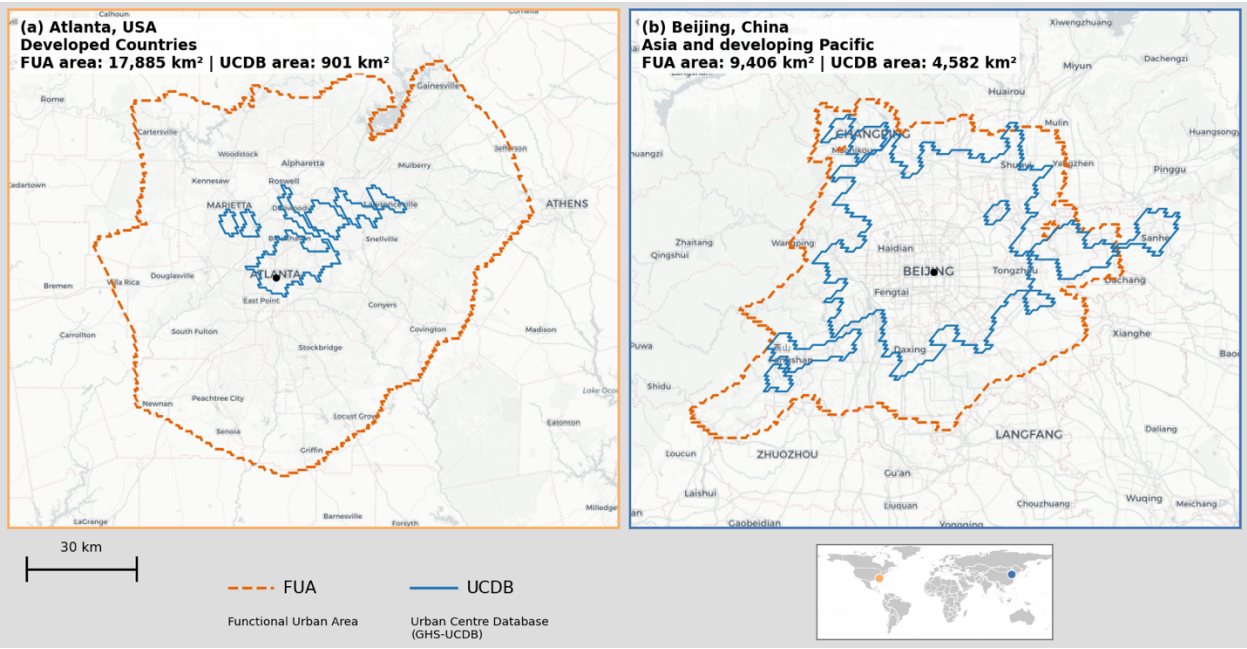

Figure S2. *Contrast between the UCDB boundary reflective of the urban "core" versus the FUA boundary.*

Text S2. Annual urban $FFCO_2$ emissions

The main text reports the most recent year, 2022, in the complete time series of absolute urban $FFCO_2$ emissions (GtC/year). Table S1 presents all years by the four boundaries and across the IPCC 6-regions and the globe.

Though not one of the urban boundaries considered in this study, we present the urban $FFCO_2$ emissions share for the Global Human Settlement Urban Centre DataBase (GHS-UCDB) boundary as a point of reference for other studies that have used this urban centre boundary for analysis (Table S2).

Table S1. *Vulcan-UrbanML $FFCO_2$ emissions by year and IPCC region for three urban boundaries.*

GUB boundary	Africa (GtC/yr)	Asia & Developing Pacific (GtC/yr)	Developed Countries (GtC/yr)	Eastern Europe & West-Central Asia (GtC/yr)	Latin America & Caribbean (GtC/yr)	Middle East (GtC/yr)	Global (GtC/yr)
2010	0.17	2.13	2.00	0.26	0.20	0.17	4.96
2011	0.17	2.32	1.95	0.27	0.20	0.17	4.97
2012	0.17	2.44	1.88	0.27	0.21	0.18	5.23
2013	0.18	2.45	1.94	0.27	0.22	0.18	5.20
2014	0.19	2.47	1.90	0.26	0.22	0.18	5.15
2015	0.18	2.52	1.86	0.26	0.22	0.20	5.18
2016	0.19	2.45	1.88	0.27	0.21	0.20	5.22
2017	0.18	2.52	1.83	0.28	0.21	0.21	5.24
2018	0.19	2.65	1.86	0.29	0.20	0.21	5.47
2019	0.20	2.77	1.82	0.28	0.20	0.21	5.39
2020	0.19	2.74	1.68	0.27	0.19	0.20	5.25
2021	0.20	2.93	1.73	0.29	0.21	0.21	5.64
2022	0.20	2.96	1.75	0.29	0.21	0.22	5.59
GCTB boundary							
2010	0.12	1.88	1.32	0.23	0.20	0.20	3.95
2011	0.12	2.08	1.30	0.25	0.21	0.21	4.16
2012	0.12	2.23	1.30	0.25	0.22	0.23	4.36
2013	0.13	2.30	1.31	0.25	0.23	0.22	4.44
2014	0.14	2.35	1.29	0.25	0.23	0.24	4.49
2015	0.13	2.38	1.28	0.25	0.23	0.25	4.53
2016	0.14	2.42	1.28	0.25	0.23	0.26	4.59
2017	0.14	2.49	1.29	0.26	0.23	0.26	4.66
2018	0.14	2.61	1.29	0.27	0.22	0.27	4.81
2019	0.15	2.69	1.26	0.26	0.22	0.28	4.87
2020	0.15	2.77	1.15	0.27	0.21	0.26	4.81
2021	0.16	2.91	1.22	0.27	0.22	0.27	5.06
2022	0.16	3.08	1.38	0.31	0.24	0.29	5.46
FUA boundary							
2010	0.14	2.15	1.68	0.22	0.25	0.23	4.77
2011	0.14	2.41	1.65	0.24	0.25	0.24	4.88
2012	0.14	2.47	1.66	0.24	0.26	0.25	4.93
2013	0.15	2.53	1.63	0.23	0.27	0.25	5.05
2014	0.16	2.55	1.61	0.23	0.27	0.26	5.09
2015	0.15	2.54	1.57	0.22	0.26	0.28	5.14
2016	0.16	2.58	1.61	0.23	0.26	0.28	5.10
2017	0.16	2.69	1.58	0.24	0.26	0.28	5.14
2018	0.16	2.77	1.59	0.25	0.25	0.29	5.24
2019	0.17	2.87	1.53	0.23	0.24	0.29	5.31
2020	0.16	2.90	1.39	0.23	0.23	0.28	5.14
2021	0.18	3.04	1.51	0.24	0.25	0.28	5.36
2022	0.18	3.09	1.50	0.26	0.25	0.30	5.42
FUGUB boundary							
2010	0.18	2.23	1.98	0.28	0.27	0.25	5.18

2011	0.19	2.43	1.93	0.30	0.27	0.25	5.37
2012	0.19	2.53	1.91	0.30	0.29	0.27	5.48
2013	0.19	2.57	1.92	0.29	0.30	0.27	5.54
2014	0.21	2.60	1.89	0.29	0.30	0.28	5.56
2015	0.20	2.62	1.87	0.29	0.29	0.29	5.55
2016	0.21	2.63	1.85	0.29	0.29	0.30	5.57
2017	0.21	2.68	1.85	0.30	0.28	0.30	5.63
2018	0.21	2.81	1.86	0.32	0.27	0.31	5.78
2019	0.22	2.90	1.82	0.30	0.26	0.31	5.81
2020	0.21	2.92	1.66	0.30	0.23	0.30	5.62
2021	0.22	3.06	1.76	0.31	0.25	0.30	5.89
2022	0.22	3.09	1.75	0.32	0.26	0.32	5.96

Table S2. *Urban share for the GHS-UCDB boundary.*

Year	Africa (%)	Asia & Developing Pacific (%)	Developed Countries (%)	Eastern Europe & West-Central Asia (%)	Latin America & Caribbean (%)	Middle East (%)	Global (%)
2010	44.4	50.7	25.8	25.5	49.2	43.3	39.1
2011	46.0	51.0	26.7	25.4	47.4	41.6	39.9
2012	43.6	51.5	26.5	25.7	47.7	44.1	40.3
2013	42.2	51.2	26.8	25.7	48.1	41.5	39.5
2014	43.0	51.1	27.0	26.3	49.2	42.1	39.6
2015	42.9	50.4	27.0	25.7	47.5	44.3	40.6
2016	44.1	51.7	27.4	27.3	48.3	46.0	40.5
2017	44.2	50.2	27.7	27.0	46.8	44.8	39.9
2018	42.3	50.5	27.7	27.3	48.0	47.9	41.0
2019	45.1	51.3	28.0	25.7	47.8	45.7	41.0
2020	44.2	52.3	28.2	26.1	50.9	44.0	42.1
2021	46.0	51.7	28.4	24.7	50.6	43.8	42.5
2022	46.4	51.6	28.2	26.6	51.9	43.5	42.6

Text S3. CDP comparison

The results produced here were compared to a collection of curated self-reported GHG emission inventory results archived by the Carbon Disclosure Project (Nangini et al., 2019). After name and surface area matching, 77 cities, out of the original 343, remained. The comparison shows a mean relative difference for the $FFCO_2$ emissions of -13.4% (±7.8%) where the relative difference is calculated as [CDP-Vulcan UrbanML]/mean[CDP,Vulcan UrbanML]. Because the extent of the urban boundary cannot be precisely matched (many of the urban self-reported inventories are restricted to nationally unique governance boundaries which are distinct from the boundaries used in this study), emissions intensity based on the urban area is also compared. This resulted in a mean relative difference of -5.1% (±8.9%). This cannot be considered a form of validation as the self-reported inventories can contain large biases and the system boundaries are not consistently reported (Gurney et al., 2021). However, the relatively close mean agreement offers a check (albeit limited) on the general integrity of the Vulcan-UrbanML results.

Table S3. *Population share, GDP share, land area share for the 2022 FUGUB boundary by IPCC region.*

Region	Pop share (%)	Urban share (%)	GDP share (%)	Area share (%)
Africa	42.8	69.2	56.9	0.50
Asia and developing Pacific	54.4	73.0	72.2	3.88
Developed Countries	82.2	69.1	82.1	3.80
Eastern Europe and West-Central Asia	67.1	56.0	68.1	0.54
Latin America and Caribbean	69.3	70.4	79.7	1.12
Middle East	66.8	63.7	79.7	1.30
Global	58.7	69.9	77.0	2.06

Table S4. *Trends of absolute urban territorial $FFCO_2$ emissions, urban share, urban per capita territorial $FFCO_2$ emissions, and absolute regional $FFCO_2$ emissions over the 2010-2022 time period by IPCC region. (± standard error in parentheses).*

Region	Urban share trend (%/yr)	Urban percap trend (%/yr)	Urban emit trend (%/yr)	Region emit trend (%/yr)
Africa	-0.28 (0.13)	-0.84 (0.14)	1.44 (0.15)	1.79 (0.23)
Asia & Developing Pacific	-0.08 (0.07)	1.43 (0.17)	2.32 (0.16)	2.41 (0.14)
Developed Countries	0.31 (0.02)	-1.56 (0.16)	-1.08 (0.16)	-1.53 (0.17)
Eastern Europe & West-Central Asia	0.11 (0.09)	0.28 (0.21)	0.77 (0.21)	0.58 (0.25)
Latin America & Caribbean	-0.42 (0.09)	-1.98 (0.41)	-1.13 (0.44)	-0.70 (0.46)
Middle East	0.21 (0.15)	0.00 (0.21)	1.93 (0.22)	1.66 (0.13)
Global	0.11 (0.03)	-0.10 (0.11)	0.90 (0.08)	0.69 (0.14)

Text S4. Method details

The urban share analysis in this study is based on a machine learning (ML) approach to estimate urban $FFCO_2$ emissions globally. This method includes different geospatial input datasets, harmonized to the same grid/pixel resolution. These datasets are aggregated to four urban polygon definitions and trained on United States Vulcan version 4.0 territorial $FFCO_2$ emissions similarly aggregated to the same urban polygon definitions across the 2010-2022 time period. Figure S3 provides a schematic overview of the workflow, Table S5 provides details on all of the input data used in the ML model, Table S6 provides model performance metrics, and Table S7 provides the relative feature performance of the various input datasets.

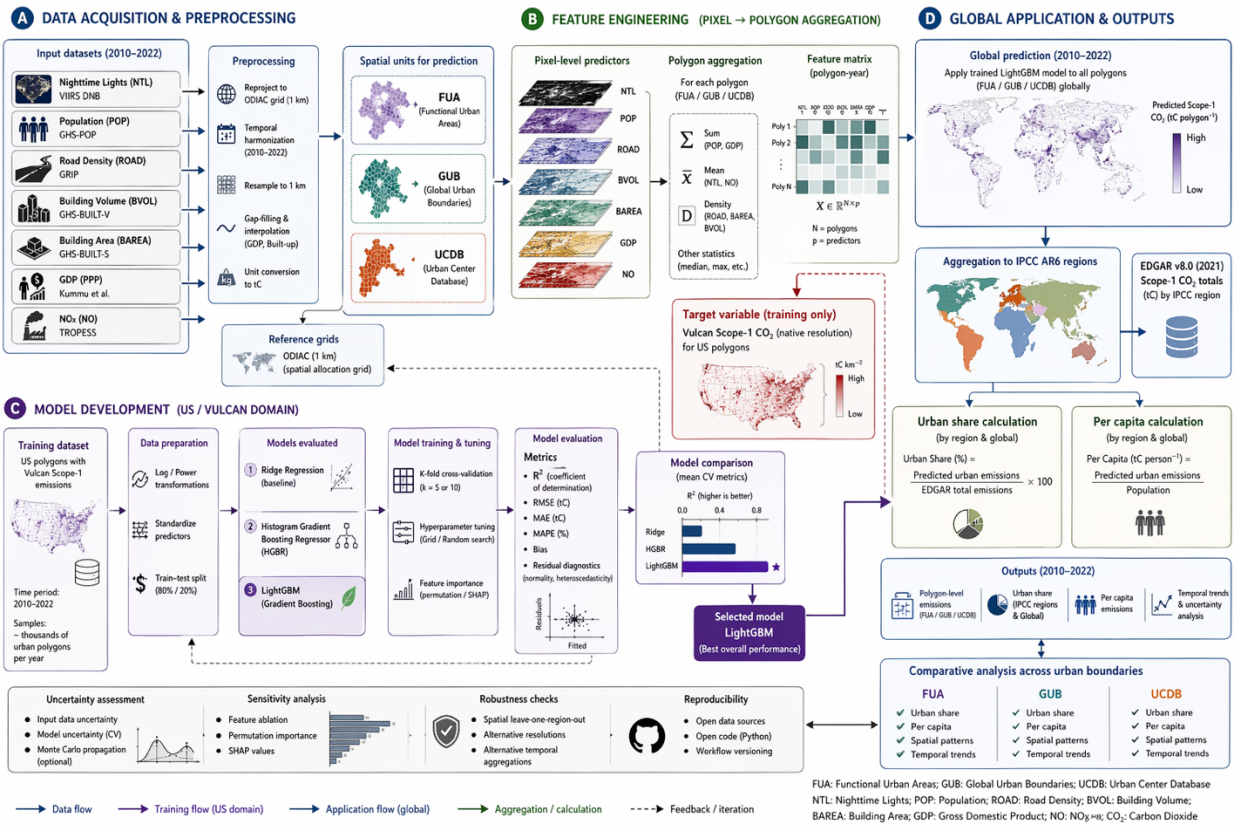

Figure S3. *Workflow for the study.*

***Table S5**. Summary of datasets used in this study.*

Variable	Data Source	Format	Resolution	Temporal Coverage	Reference
Nighttime Lights (radiance)	VIIRS DNB	Raster (GeoTIFF)	~500 m	2012–present (2010 & 2011 set to 2012 value)	(Elvidge et al., 2017)
Population count	GHS-POP	Raster (GeoTIFF)	1 km	2010, 2015, 2020, 2025 (interpolated to annual)	(Pesaresi et al., 2024)
Road Density	GRIP v4	Raster (ASCII)	~5 km	Static	(Meijer et al., 2018)
Built Volume	GHS-BUILT-V	Raster (GeoTIFF)	1 km	2010, 2015, 2020, 2025 (interpolated to annual)	(Pesaresi et al., 2024)
Built Area	GHS-BUILT-S	Raster (GeoTIFF)	1 km	2010, 2015, 2020, 2025 (interpolated to annual)	(Pesaresi et al., 2024)
GDP (PPP-adjusted)	GDP grid	NetCDF	~1 km	2010-2015 (2016-2022 set to 2015 value)	(Kummu et al., 2018)
NOx: Nitrogen oxides emissions	TROPESS reanalysis	NetCDF	~1.125°	2005–2021 (2022 set to 2021 value)	(Worden & others, 2022)
Territorial $FFCO_2$ emissions	Vulcan v4	Point, line, polygon	Lowest: U.S. Census block	2010–2022	(Gurney et al., 2025)
Global/regional emission totals	EDGAR v8.0*	Tabular	Country	1970–2022	(Crippa et al., 2024)

*for estimating the consumption-based urban share, the regional and global totals include both anthropogenic CO_2 and CH_4 from the EDGAR national/global results.

***Table S6.** Light GBM machine learning model performance.*

Boundary	R^2	RMSE (MtC)	MAE (MtC)	Bias (MtC)	MPE	MAPE
GUB	0.82	2.0	1.4	1.8	3.4	2.8
GCTB	0.82	2.01	1.3	1.7	3.3	2.8
FUA	0.86	1.9	1.1	1.1	2.1	2.4
FUGUB	0.81	2.0	1.3	1.3	3.1	2.7

RMSE: root mean square error
MAE: mean absolute error
BIAS: mean error
MPE: mean percent error
MAPE: mean absolute percent error

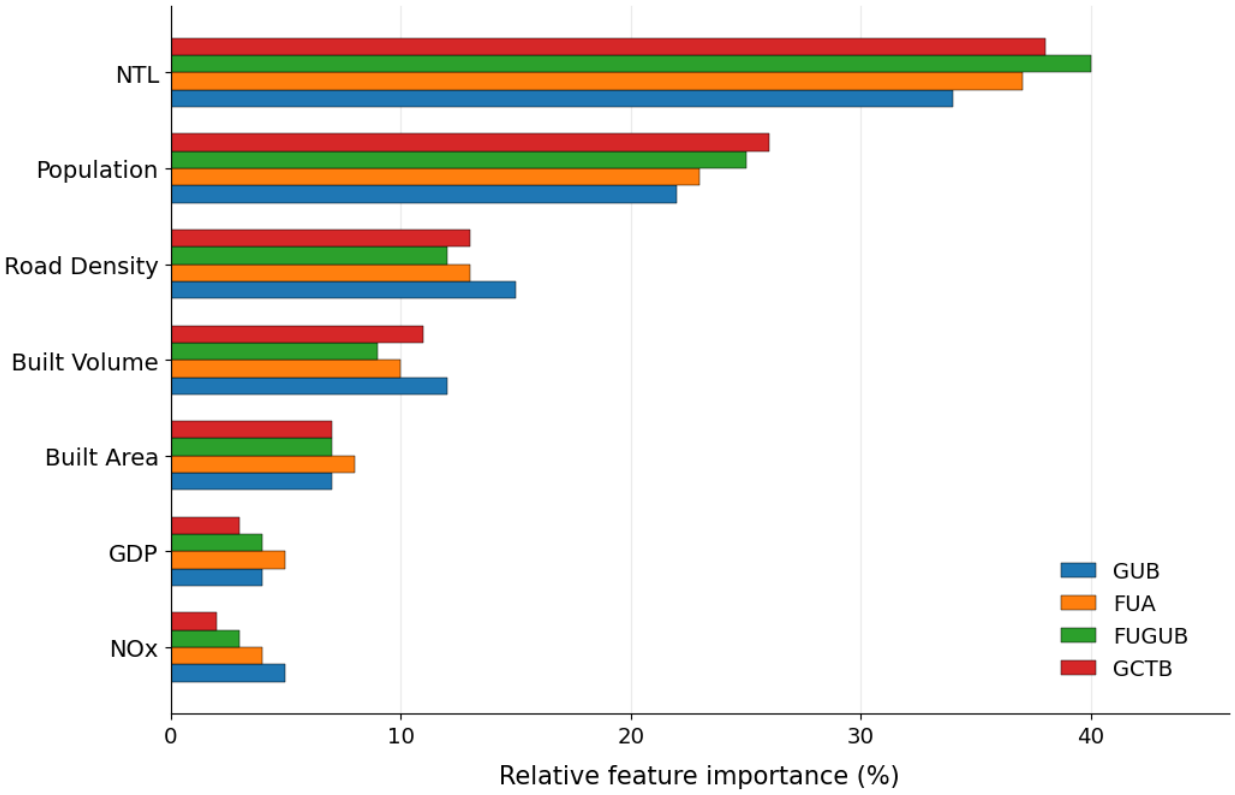

Figure S4. *Feature importance of the input variables to the Vulcan-UrbanML model trained on the four urban boundaries.*

Table S7. *IPCC AR6 6-region country listing.*

ISO	Name	AR6_6 Region
AFG	Afghanistan	Asia and developing Pacific
ALA	Åland Islands	Developed Countries
ALB	Albania	Developed Countries
DZA	Algeria	Africa
ASM	American Samoa	Asia and developing Pacific
AND	Andorra	Developed Countries
AGO	Angola	Africa
AIA	Anguilla	Latin America and Caribbean
ATG	Antigua and Barbuda	Latin America and Caribbean
ARG	Argentina	Latin America and Caribbean
ARM	Armenia	Eastern Europe and West-Central Asia
ABW	Aruba	Latin America and Caribbean
AUS	Australia	Developed Countries
AUT	Austria	Developed Countries
AZE	Azerbaijan	Eastern Europe and West-Central Asia
BHS	Bahamas, The	Latin America and Caribbean
BHR	Bahrain	Middle East
BGD	Bangladesh	Asia and developing Pacific
BRB	Barbados	Latin America and Caribbean
BLR	Belarus	Eastern Europe and West-Central Asia
BEL	Belgium	Developed Countries
BLZ	Belize	Latin America and Caribbean
BEN	Benin	Africa
BMU	Bermuda	Developed Countries
BTN	Bhutan	Asia and developing Pacific
BOL	Bolivia	Latin America and Caribbean
BES	Bonaire, Sint Eustatius and Saba	Latin America and Caribbean

BIH	Bosnia and Herzegovina	Developed Countries
BWA	Botswana	Africa
BRA	Brazil	Latin America and Caribbean
VGB	British Virgin Islands	Latin America and Caribbean
BRN	Brunei Darussalam	Asia and developing Pacific
BGR	Bulgaria	Developed Countries
BFA	Burkina Faso	Africa
BDI	Burundi	Africa
CPV	Cabo Verde	Africa
KHM	Cambodia	Asia and developing Pacific
CMR	Cameroon	Africa
CAN	Canada	Developed Countries
CYM	Cayman Islands	Latin America and Caribbean
CAF	Central African Republic	Africa
TCD	Chad	Africa
CHL	Chile	Latin America and Caribbean
CHN	China	Asia and developing Pacific
COL	Colombia	Latin America and Caribbean
COM	Comoros	Africa
COD	Congo, Dem. Rep.	Africa
COG	Congo, Rep.	Africa
COK	Cook Islands	Asia and developing Pacific
CRI	Costa Rica	Latin America and Caribbean
CIV	Côte d'Ivoire	Africa
HRV	Croatia	Developed Countries
CUB	Cuba	Latin America and Caribbean
CUW	Curaçao	Latin America and Caribbean
CYP	Cyprus	Developed Countries
CZE	Czech Republic	Developed Countries
DNK	Denmark	Developed Countries
DJI	Djibouti	Africa
DMA	Dominica	Latin America and Caribbean
DOM	Dominican Republic	Latin America and Caribbean
ECU	Ecuador	Latin America and Caribbean
EGY	Egypt, Arab Rep.	Africa
SLV	El Salvador	Latin America and Caribbean
GNQ	Equatorial Guinea	Africa
ERI	Eritrea	Africa
EST	Estonia	Developed Countries
ETH	Ethiopia	Africa
FJI	Fiji	Asia and developing Pacific
FIN	Finland	Developed Countries
FRA	France	Developed Countries
GUF	French Guiana	Latin America and Caribbean
PYF	French Polynesia	Asia and developing Pacific
GAB	Gabon	Africa
GMB	Gambia, The	Africa
GEO	Georgia	Eastern Europe and West-Central Asia
DEU	Germany	Developed Countries
GHA	Ghana	Africa
GIB	Gibraltar	Developed Countries
GRC	Greece	Developed Countries
GRL	Greenland	Developed Countries
GRD	Grenada	Latin America and Caribbean
GLP	Guadeloupe	Latin America and Caribbean
GUM	Guam	Asia and developing Pacific
GTM	Guatemala	Latin America and Caribbean
GGY	Guernsey	Developed Countries
GIN	Guinea	Africa
GNB	Guinea-Bissau	Africa
GUY	Guyana	Latin America and Caribbean
HTI	Haiti	Latin America and Caribbean
HND	Honduras	Latin America and Caribbean
HKG	Hong Kong SAR, China	Asia and developing Pacific
HUN	Hungary	Developed Countries
ISL	Iceland	Developed Countries

IND	India	Asia and developing Pacific
IDN	Indonesia	Asia and developing Pacific
IRN	Iran, Islamic Rep.	Middle East
IRQ	Iraq	Middle East
IRL	Ireland	Developed Countries
IMN	Isle of Man	Developed Countries
ISR	Israel	Middle East
ITA	Italy	Developed Countries
JAM	Jamaica	Latin America and Caribbean
JPN	Japan	Developed Countries
JEY	Jersey	Developed Countries
JOR	Jordan	Middle East
KAZ	Kazakhstan	Eastern Europe and West-Central Asia
KEN	Kenya	Africa
KIR	Kiribati	Asia and developing Pacific
PRK	Korea, Dem. People's Rep.	Asia and developing Pacific
KOR	Korea, Rep.	Asia and developing Pacific
KWT	Kuwait	Middle East
KGZ	Kyrgyz Republic	Eastern Europe and West-Central Asia
LAO	Lao PDR	Asia and developing Pacific
LVA	Latvia	Developed Countries
LBN	Lebanon	Middle East
LSO	Lesotho	Africa
LBR	Liberia	Africa
LBY	Libya	Africa
LIE	Liechtenstein	Developed Countries
LTU	Lithuania	Developed Countries
LUX	Luxembourg	Developed Countries
MAC	Macao SAR, China	Asia and developing Pacific
MKD	North Macedonia	Eastern Europe and West-Central Asia
MDG	Madagascar	Africa
MWI	Malawi	Africa
MYS	Malaysia	Asia and developing Pacific
MDV	Maldives	Asia and developing Pacific
MLI	Mali	Africa
MLT	Malta	Developed Countries
MHL	Marshall Islands	Asia and developing Pacific
MTQ	Martinique	Latin America and Caribbean
MRT	Mauritania	Africa
MUS	Mauritius	Africa
MYT	Mayotte	Africa
MEX	Mexico	Latin America and Caribbean
FSM	Micronesia, Fed. Sts.	Asia and developing Pacific
MDA	Moldova	Eastern Europe and West-Central Asia
MCO	Monaco	Developed Countries
MNG	Mongolia	Asia and developing Pacific
MNE	Montenegro	Developed Countries
MSR	Montserrat	Latin America and Caribbean
MAR	Morocco	Africa
MOZ	Mozambique	Africa
MMR	Myanmar	Asia and developing Pacific
NAM	Namibia	Africa
NRU	Nauru	Asia and developing Pacific
NPL	Nepal	Asia and developing Pacific
NLD	Netherlands	Developed Countries
NCL	New Caledonia	Asia and developing Pacific
NZL	New Zealand	Developed Countries
NIC	Nicaragua	Latin America and Caribbean
NER	Niger	Africa
NGA	Nigeria	Africa
NIU	Niue	Asia and developing Pacific
NOR	Norway	Developed Countries
OMN	Oman	Middle East
PAK	Pakistan	Asia and developing Pacific
PLW	Palau	Asia and developing Pacific
PAN	Panama	Latin America and Caribbean

PNG	Papua New Guinea	Asia and developing Pacific
PRY	Paraguay	Latin America and Caribbean
PER	Peru	Latin America and Caribbean
PHL	Philippines	Asia and developing Pacific
POL	Poland	Developed Countries
PRT	Portugal	Developed Countries
PRI	Puerto Rico	Latin America and Caribbean
QAT	Qatar	Middle East
REU	Réunion	Africa
ROU	Romania	Developed Countries
RUS	Russian Federation	Eastern Europe and West-Central Asia
RWA	Rwanda	Africa
WSM	Samoa	Asia and developing Pacific
SMR	San Marino	Developed Countries
STP	São Tomé and Principe	Africa
SAU	Saudi Arabia	Middle East
SEN	Senegal	Africa
SRB	Serbia	Developed Countries
SYC	Seychelles	Africa
SLE	Sierra Leone	Africa
SGP	Singapore	Asia and developing Pacific
SVK	Slovak Republic	Developed Countries
SVN	Slovenia	Developed Countries
SLB	Solomon Islands	Asia and developing Pacific
SOM	Somalia	Africa
ZAF	South Africa	Africa
SSD	South Sudan	Africa
ESP	Spain	Developed Countries
LKA	Sri Lanka	Asia and developing Pacific
SDN	Sudan	Africa
SUR	Suriname	Latin America and Caribbean
SWE	Sweden	Developed Countries
CHE	Switzerland	Developed Countries
SYR	Syrian Arab Republic	Middle East
TWN	Taiwan, China	Asia and developing Pacific
TJK	Tajikistan	Eastern Europe and West-Central Asia
TZA	Tanzania	Africa
THA	Thailand	Asia and developing Pacific
TLS	Timor-Leste	Asia and developing Pacific
TGO	Togo	Africa
TON	Tonga	Asia and developing Pacific
TTO	Trinidad and Tobago	Latin America and Caribbean
TUN	Tunisia	Africa
TUR	Turkey	Developed Countries
TKM	Turkmenistan	Eastern Europe and West-Central Asia
TCA	Turks and Caicos Islands	Latin America and Caribbean
TUV	Tuvalu	Asia and developing Pacific
UGA	Uganda	Africa
UKR	Ukraine	Developed Countries
ARE	United Arab Emirates	Middle East
GBR	United Kingdom	Developed Countries
USA	United States	Developed Countries
URY	Uruguay	Latin America and Caribbean
UZB	Uzbekistan	Eastern Europe and West-Central Asia
VUT	Vanuatu	Asia and developing Pacific
VEN	Venezuela, RB	Latin America and Caribbean
VNM	Vietnam	Asia and developing Pacific
VIR	Virgin Islands (U.S.)	Latin America and Caribbean
PSE	West Bank and Gaza	Middle East
ESH	Western Sahara	Africa
YEM	Yemen, Rep.	Middle East
ZMB	Zambia	Africa
ZWE	Zimbabwe	Africa

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