

1 **A high-resolution, spatially explicit estimate of fossil-fuel CO₂**
2 **emissions from the Tokyo Metropolis, Japan**

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10 **Abstract**

11 **Background:** The quantification of urban greenhouse gas (GHG) emissions is an important
12 task in combating climate change. Emission inventories that include spatially explicit
13 emission estimates facilitate the accurate tracking of emission changes, identification of
14 emission sources, and formulation of policies for climate-change mitigation. Many currently
15 available gridded emission estimates are based on the disaggregation of country- or state-
16 wide emission estimates, which may be useful in describing city-wide emissions but are of
17 limited value in tracking changes at subnational levels. Urban GHG emissions should
18 therefore be quantified with a true bottom-up approach.

19 **Results:** Multi-resolution, spatially explicit estimates of fossil-fuel carbon dioxide (FFCO₂)
20 emissions from the Tokyo Metropolis, Japan, were derived. Spatially explicit emission data
21 were collected for point (e.g., power plants and waste incinerators), line (mostly traffic), and
22 area (e.g., residential and commercial areas) sources. Emissions were mapped on the basis of
23 emission rates calculated for source locations. Activity, emissions, and spatial data were
24 integrated, and the results were visualized using a geographic information system approach.

25 **Conclusions:** The annual total FFCO₂ emissions from the Tokyo Metropolis in 2014 were
26 43,916 Gg CO₂, with the road-transportation sector (16,323 Gg CO₂) accounting for 37.2% of
27 the total. Spatial emission patterns were verified via a comparison with the East Asian Air
28 Pollutant Emission Grid Database for Japan (EAGrid-Japan) and the Open-source Data
29 Inventory for Anthropogenic CO₂ (ODIAC), which demonstrated the applicability of this
30 methodology to other prefectures and therefore the entire country.

31

32 Keywords: Carbon dioxide, CO₂ emission inventory, Fossil fuel, GIS, High-resolution map,
33 Tokyo emissions

34 **Background**

35 Fossil-fuel combustion is a major contributor to increasing atmospheric carbon dioxide (CO₂)
36 concentrations [1], with cities worldwide being responsible for more than 70% of the global
37 total fossil-fuel CO₂ emissions (FFCO₂) [2]. As large sources of FFCO₂, cities have great
38 potential for emission mitigation [3]. In response to the need for local climate action, many
39 global cities have participated in climate action groups, such as the C40 Cities Climate
40 Leadership Group [4] and the Global Covenant of Mayors for Climate & Energy [5], and
41 started compiling emission inventories (EIs). The EIs are often compiled following the
42 Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) [6].
43 The Paris Agreement of the United Nations Framework Convention on Climate Change
44 (UNFCCC) recognizes the importance of climate-change mitigation at subnational levels [7].
45 However, subnational emission estimates (e.g., state, province, city (UN-Habitat [2]), and
46 private sector) are beyond the scope of the current Intergovernmental Panel on Climate
47 Change (IPCC) guidelines. The inventory framework implemented under the Kyoto Protocol
48 focuses on national compliance with global emission-reduction targets [8], rather than
49 monitoring emission changes at subnational levels.

50 Cities play an important role for implementation of climate-remediation actions. Previous
51 studies have accounted for city emissions using various approaches, including the purely
52 geographic-based (PB) [9, 10], consumption-based carbon-footprint [11, 12], and
53 community-wide infrastructure-footprint [13, 14] approaches. Such studies estimate
54 emissions for whole cities by monitoring activities at the city level. Due to recent mitigation
55 action, the need for more detailed information on temporospatial distributions of emissions
56 has increased, necessitating the assessment of emission changes at sub-city levels.
57 For spatially explicit emission data, Gurney et al. [15] loosely categorized emission modeling
58 approaches as ‘downscaled’ or ‘bottom-up’. The downscaled approach is used mainly for
59 global-scale greenhouse gas (GHG) EIs, and downscales national total emissions to source-
60 related proxies [16, 17, 18]. Conversely, the bottom-up approach estimates temporospatially
61 explicit emissions based on sectoral activity data derived from socioeconomic sources. These
62 two approaches result in large discrepancies in urban-scale FFCO₂ emissions, due to the
63 limitations of downscaled EIs in capturing spatial patterns of complex source activities [19].
64 Since the bottom-up approach considers local-scale emission sources, emission estimates
65 based on this approach are likely suitable for tracking emission changes in sub-city and local
66 areas. For example, the Hestia Project developed multi-resolution emission data for four US
67 cities using a bottom-up approach [20-23]. These EIs provide bottom-up FFCO₂ emission
68 data for the urban domain with building/street and hourly temporospatial resolution. GHG
69 emissions for Poland and Ukraine were estimated based on geoinformation technologies,
70 where emissions were determined at source locations (points, lines, and areas), taking into
71 account emission processes [24]. This approach enables the tracking of changes in local
72 emissions, allowing the evaluation of existing EIs over the domain of a single country [24,
73 25]. Limited by the availability of fossil fuel use from individual sources, previous studies
74 succeeded in disaggregating the reported CO₂ annual emissions/fuel use from a larger scale
75 e.g., county/provincial level to individual sources/proxies for temporospatially explicit
76 estimates (Table1). This study also uses disaggregating processes for area-sources, however,
77 the annual emissions by point and line sources are directly estimated for individual
78 sources/proxies without disaggregation, by integrating spatially-explicit statistics data with
79 region-specific secondary-derived emission factors.

80 This study presents a detailed framework for the direct accounting of local FFCO₂ emissions
81 in Japan using a bottom-up approach (i.e., PB approach for direct emissions (Scope-1) [6])
82 and demonstrates its application to multi-resolution emissions at point, road, building, or
83 mesh levels. As a pilot study, we first consider spatially explicit FFCO₂ emission data for the
84 Tokyo Metropolis (population 13.6 M in 2016; area 2,189 km²) for the year 2014. This study
85 is distinguished from the East Asian Air Pollutant Emission Grid Database for Japan
86 (EAGrid-Japan) by the use of a multi-resolution approach and updated information. Here, we
87 describe the various statistical and geospatial data used in estimating and mapping emissions,
88 compare our emission estimates with existing estimates at aggregated city and grid cell
89 levels, and discuss current limitations and future improvements.

90

91 **Methods**

92 **Emission definition and modeling framework**

93 The focus here is on quantifying FFCO₂ emissions from the Tokyo Metropolis using the
94 modeling framework described in Fig. 1. Following previous studies [20, 24, 32], a multi-
95 resolution emission modeling approach was employed, where CO₂ emissions (‘emissions’
96 hereinafter) were calculated on an individual source basis in a bottom-up manner, rather than
97 using aggregated emission-sector levels. Emissions were spatially allocated using verified
98 geographic latitude and longitude coordinates (mainly for point sources) and spatial
99 geolocation data (for line and area sources), with examples of point-source locations and
100 geospatial data shown in Fig. 2.

101 The total emissions for the year 2014 were calculated using the best available locally
102 collected data following the 2006 IPCC guidelines [33]. Emission sources therefore included
103 electricity generation (IPCC code 1A1ai), civil aviation (1A3a), waterborne navigation
104 (1A3d), waste incineration (4C1), road transportation (1A3bi, 1A3bii, and 1A3biii), industrial
105 and commercial sources (1A1aiii, 1A2, 1A4a, and 1A4ciii), residential sources (1A4b), and
106 agricultural machine use (1A4cii). These emissions were calculated using the Tier 3 approach
107 [33]. The emission-sector definitions, spatial information and data, activity data, and
108 emission factors are summarized in Table 2.

109

110 **Point-source emissions**

111 Point-source emissions include those from electricity generation, civil aviation, waterborne
112 navigation, and waste incineration (Table 2). For electricity generation, only fossil-fueled
113 power plants in Tokyo ($n = 19$) were considered (see Additional File 1; Table S1 for details).
114 The 2014 total emissions from all power plants were calculated by formula:

$$115 \quad E_{eg} = 24 \cdot \sum_{i=1}^n \sum_{j=1}^{12} C_i \cdot D_j \cdot R_{g,j} \cdot EF_{g,j}, \quad (1)$$

116 where E_{eg} represents the total annual emissions from electricity generation (Gg CO₂); the
117 coefficient 24 indicates the number of hours per day; C_i is the electricity generation capacity
118 (kW) of power plant i in Tokyo with one type of generator (steam, gas cogeneration, or
119 internal combustion); D_j is the number of days in month j ; $R_{g,j}$ is the mean utilization
120 efficiency of fossil-fueled power plants with generator type g in month j for 2014; and $EF_{g,j}$
121 is the emission factor for fossil-fueled electricity generation by generator type g in month j
122 (Gg CO₂ kWh⁻¹). The C_i values were obtained from the Electrical Japan Database (data were
123 collected in April 2017) [34] and operator companies [35–37]. The $R_{g,j}$ values are reported
124 by power plant operators and published by the government of Japan each year [38]. The
125 emission factors of power plants in 2014 ($EF_{g,j}$) were derived from electricity generation
126 amounts by power plants, the monthly fuel consumption (e.g., coal, crude oil, heavy oil, light
127 oil, liquefied natural gas, liquefied petroleum gas, and other gas) [39], and official guidelines
128 for GHG emissions counting [40]. Where there was a lack of individual data for a plant, R_j
129 and EF_j values for plants with the same type of generator were used. The stack centroid was
130 used as the representative emission location for multiple smoke stacks in a single power plant
131 facility. An example of point-source emissions in SG Ward (see Table S2) is shown in Fig.
132 2A.

133 Civil aviation emissions included those from passenger and cargo aircraft during landing and
 134 take-off (LTO) at an international airport, four helipads, and six domestic airports (Table S1).
 135 The 2014 total emissions from LTO movements were calculated as follows:

$$136 \quad E_{ca} = \sum_{i=1}^n \sum_a F_{a,i} \cdot N_a \cdot EC_e \cdot EF_f, \quad (2)$$

137 where E_{ca} represents the total annual emissions from civil aviation (Gg CO₂); $F_{a,i}$ is the total
 138 number of arrivals for type a aircraft with one type of engine at airport i in 2014; N_a is the
 139 number of engines on type a aircraft; EC_e is the jet fuel ('energy') consumption per engine
 140 during an LTO cycle by engine type e (Gg per engine per LTO); and EF_f is the emission
 141 factor of jet fuel (3.154 Gg CO₂ Gg⁻¹) [40]. The $F_{a,i}$ and N_a values were summarized from
 142 2014 flight records [41–49] and websites [50]. The monthly proportion of aircraft types at
 143 Haneda airport was used as the annual proportion for 2014 due to the lack of annual flight
 144 timetables for each aircraft type. The monthly proportions of arrivals for each aircraft type
 145 were obtained from flight timetables for April 2017 [51, 52]. The EC_e values were extracted
 146 from the Aircraft Engine Emissions Databank of the International Civil Aviation
 147 Organization (ICAO) [53] and guidance on helicopter emissions [33, 54]. As aircraft are
 148 mobile sources, the calculated emissions were mapped using representative points on airport
 149 runways (diameter ~1 km) as point sources.

150 Emissions from the waterborne navigation sector included emissions from fuel consumed by
 151 vessels during round trips to ports in Tokyo ($n = 15$; Table S1). The 2014 total emissions
 152 from vessels were calculated as follows:

$$153 \quad E_{wn} = \sum_{i=1}^n \sum_{t,m} I_{t,m} \cdot R_{t,m} \cdot T_{t,m} \cdot N_{t,i} \cdot EF_t, \quad (3)$$

154 where E_{wn} represents the total annual emissions by vessels (Gg CO₂); $I_{t,m}$ is the emission
 155 intensity of fuels (tonne per vessel) for type t vessels (including merchant vessels, car ferries,
 156 evacuation vessels, fishing vessels, and other vessels) at mode m (travelling, cargo loading
 157 and unloading, and mooring); $R_{t,m}$ is the load factor of type- t vessels in mode m ; $T_{t,m}$ is the
 158 fuel consumption time of type- t vessels in mode m (h); $N_{t,i}$ is the annual number of type- t
 159 vessels travelling to port i ; and EF_t is the emission factor (Gg CO₂ tonne⁻¹) for type- t vessels
 160 consuming heavy oil or light oil. The $I_{t,m}$, $R_{t,m}$, and $T_{t,m}$ values and the average travel speed
 161 for these vessels were obtained from technical reports [55, 56]. As shown by the parameters
 162 listed in Table S3, the mean travel distance was assumed to be 1 km in travelling mode to
 163 derive the travel time. The emissions from travelling mode were considered for fishing
 164 vessels but all mode were considered for the other types of vessels. The $N_{t,i}$ values were
 165 obtained from statistical data on vessels in ports [57, 58]. The EF_t data were extracted from
 166 the official guideline [40]. As waterborne vessels are mobile sources, representative points on
 167 port buildings were used as their point-source locations.

168 Emissions from incineration plants do not contribute to FFCO₂ emissions. However, this
 169 study included their emissions because the emission intensity is significant. Emissions from
 170 incineration plants for municipal solid waste (MSW, $n = 46$) and industrial waste ($n = 15$)
 171 (Table S1) included those from the combustion of wastes containing carbon (e.g., papers,
 172 plastics, textiles, rubbers, and oil) and the combustion agent (CA, "city gas" comprising
 173 liquid petroleum gas and natural gas). Emissions from MSW waste combustion were
 174 calculated as follows:

$$175 \quad E_{mw} = \sum_{i=1}^n (\sum_c T_i \cdot R_{c,i} \cdot FC \cdot EF_c + T_i \cdot CR \cdot EF), \quad (4)$$

176 where E_{mw} represents the 2014 total emissions from MSW incineration (Gg CO₂); T_i is the
 177 total amount of combustible content in waste (tonne) incinerated annually at plant i ; $R_{c,i}$ is
 178 the proportion of type- c content of waste (i.e., waste paper, plastic, rubber, and textiles in
 179 MSW) at plant i ; FC is the fossil carbon content in waste; EF_c is the emission factor for
 180 combustible content type c in waste (paper 1.69×10^{-5} ; plastic 2.55×10^{-3} ; textiles 2.29×10^{-3} ;
 181 rubber 1.72×10^{-3} Gg CO₂ tonne⁻¹) [40]; CR is the mean consumption of CA (1.29 m³
 182 tonne⁻¹) [59]; and EF is the emission factor for CA (2.21×10^{-6} Gg CO₂ m⁻³) [40]. The T_i
 183 and $R_{c,i}$ values for all 46 MSW incineration plants in Tokyo were obtained from the
 184 investigation report on MSW for Tokyo, 2014 [60]. Here we assumed that paper and textiles
 185 in wastes were in equal amounts and the fossil carbon content (FC) of these wastes were
 186 50%. The CR values derived from available data for 19 MSW incineration plants in Tokyo
 187 [59] were used for all MSW incineration plants.

188 Emissions from industrial waste combustion were calculated as follows:

$$189 \quad E_{iw} = \sum_c T_c \cdot FC \cdot EF_c, \quad (5)$$

190 where E_{iw} represents the 2014 total emissions from industrial waste incineration (Gg CO₂);
 191 T_c is the total annual amount of combustible content in waste (tonnes) at all plants in Tokyo
 192 for type c (i.e., waste paper, plastic, textiles, and oil in industrial waste); and EF_c is the
 193 emission factor for fossil carbon in waste type c (oil 2.92×10^{-3} Gg CO₂ tonne⁻¹) [40]. T_c
 194 values were extracted from the investigation report on industrial waste incineration [61]. The
 195 FC value for industrial waste was assumed to be 1 with no CA used due to the high-purity
 196 carbon content. The emissions from 15 industrial-waste incineration plants were derived by
 197 allocating the E_{iw} with plant disposal capacities [62]. The central points of the chimneys at
 198 waste incineration plants were mapped as emission points.

200 **Line-source emissions**

201 Line-source emissions included those of the road-transport sector, based on traffic census
 202 data compiled by the Ministry of Land, Infrastructure, Transport and Tourism for each
 203 prefecture every five years, with the latest being in 2015 [63]. The census data include road
 204 information (name, width, length, number of lanes, and classification for each road segment),
 205 hourly and daily traffic volumes, and 12-h mean daytime vehicle speeds for small vehicles
 206 (light passenger cars, regular passenger cars, light trucks, and small freight cars) and large
 207 vehicles (bus, regular truck, and special-use vehicles). The road segment data indicate the
 208 network links, as shown in the example of a digital road map (DRM; [64]) in Fig. 2B. The
 209 census targets five road classifications: high-speed national highways, urban highways,
 210 general national highways, major regional roads (prefectural roads and designated city roads),
 211 and general regional roads. Emissions on minor roads that were not covered by the census
 212 were not considered.

213 Road transportation emissions were calculated for single road segments ($n = 45,564$) as
 214 follows:

$$215 \quad E_{rt} = \sum_{i=1}^n \sum_v Q_{v,i} \cdot L_i \cdot EF_{v,s}, \quad (6)$$

216 where E_{rt} represents the 2014 total emissions from road transportation (Gg CO₂); $Q_{v,i}$ is the
 217 annual traffic volume (derived from daily data) for type v vehicles at a vehicle speed (from 5
 218 to 90 km/h) on road segment i ; L_i is the length of road segment i (km); $EF_{v,s}$ is the emission

219 factor for type- v vehicles by vehicle speed s (Gg CO₂ km⁻¹ per vehicle). The census
 220 identification numbers for road segments were used with Google Maps software to select
 221 point coordinates for each observed road segment, with the selected points being mapped to
 222 identify the same roads on the DRM. The information from the traffic census, such as road
 223 classification, daily traffic volume, and mean speed, were combined for the DRM road
 224 segments. The average traffic conditions for each road classification in each municipality unit
 225 [65] were substituted for the road segments not covered by the census. The L_i values were
 226 calculated from the DRM using a geographic information system (GIS) tool. The $EF_{v,s}$ values
 227 were obtained from Dohi et al. [66] (Table 3). Emissions were mapped on the center line of
 228 each road segment.

230 **Area-source emissions**

231 Area-source emissions included those from the industrial, commercial, residential, and
 232 agricultural sectors. The main source of industrial, commercial, and residential emissions is
 233 fuel consumption in buildings, for which the Hestia project [23] estimated non-electrical
 234 energy using the eQUEST simulation tool [67] by incorporating the building classification
 235 and age, with the building emissions based on the building total floor areas (TFAs) [68].
 236 Since spatial data (building polygons) are not available for buildings of all ages in Japan,
 237 census data were used to allocate the emissions using building polygons (Fig. 2C) based on
 238 the TFAs.

239 Emissions from the industrial and commercial sector included those from fossil-fuel
 240 consumption by workers. Emissions from all areas in Tokyo, based on the economic census
 241 ($n = 5,318$), were calculated as follows:

$$242 \quad E_{ic} = \sum_{i=1}^n \sum_q W_{q,i} \cdot \frac{TE_q}{TW_q}, \quad (7)$$

243 where E_{ic} represents the 2014 total emissions from the industrial and commercial sector (Gg
 244 CO₂); $W_{q,i}$ is the number of workers for category q in census area i (Table 4); TE_q is the total
 245 annual emissions for category q (Gg CO₂); and TW_q is the total number of workers in category
 246 q . The $W_{q,i}$ values for all of the categories in census areas were obtained from the 2014
 247 economic census [69]. The census area comprised politically based blocks with an average area
 248 of around 0.5 km². The TW_q values were obtained from economic census data [69], and the
 249 TE_q values were extracted from the Tokyo energy-balance table [70]. The annual CO₂ emission
 250 factors by workers ($\frac{TE_q}{TW_q}$; Gg CO₂ per worker) were derived for each category (Table 4). The
 251 annual emissions from the fuels used in energy conversion (e.g., electricity generation and
 252 waste incineration) were not included in the energy-balance table [70] to avoid counting them
 253 twice. The reported total emissions for the industrial and commercial sector were used to derive
 254 emission factors and to calculate the emissions for each census area, similar to the approach
 255 used by Gately and Hutyra (2017) [19] for commercial emissions.

256 Total emissions were allocated to individual buildings in each census area, with all of the
 257 building polygons being associated to a given building use (industrial and commercial, or
 258 residential), using land-use maps covering four areas (23 wards in Tokyo, the Tama city area,
 259 Tama rural area, and island areas) at spatial resolutions of 3×3 m to 43×43 m [71]. The
 260 data on individual building polygons (e.g., site area (m²), height (m), number of floors, and

261 floor area (m²) were obtained as follows. Each building site area was estimated from the
 262 building polygon maps, and the building height was estimated from the difference in heights
 263 between a raster-type digital surface model (DSM) [72] and a vector-type digital-elevation
 264 model (DEM) [73]. DSM v. 1.1 was based on digital photos from the Advanced Land
 265 Observing Satellite, with an accuracy within 5 m [72]. A 30 × 30 m DSM dataset was used
 266 with a 5 × 5 m DEM dataset (updated in 2016) based on airborne laser observations (2015),
 267 with an elevation accuracy within 0.7 m (standard deviation) [73]. The number of floors was
 268 estimated by dividing the building height by the average ceiling height (2.9 m for residential
 269 buildings, and 3.5 m for industrial and commercial buildings). The TFAs were estimated by
 270 multiplying the site area by the number of floors. The emission factors of the buildings (Gg
 271 CO₂ m⁻²) in each census area were calculated by dividing the total emissions by the TFAs,
 272 aggregated over the census areas. Finally, the emissions from each industrial and commercial
 273 building were estimated by multiplying the emission factors by the TFAs of the individual
 274 buildings. Industrial and commercial emissions were mapped at the level of individual
 275 buildings.

276 Emissions from the residential sector were calculated for all of the population census areas in
 277 Tokyo ($n = 5,578$) by formula:

$$278 \quad E_{re} = \sum_{i=1}^n \sum_{f,h,b} A_{h,b,i} \cdot EF_{f,h,b}, \quad (8)$$

279 where E_{re} represents the 2014 total emissions from the residential sector (Gg CO₂); $A_{h,b,i}$ is
 280 the number of households with occupancy h (with four categories: 1, 2, 3, or ≥ 4 occupants) in
 281 type b buildings (collective or detached) in the census area i ; and $EF_{f,h,b}$ is the total annual
 282 emission intensity (Gg CO₂ yr⁻¹ per household) of fuel type f , in household with occupancy
 283 h , and for building type b . The $A_{h,b,i}$ values were obtained from the 2015 population census
 284 data [74], and the $EF_{f,h,b}$ were from an investigation report on energy consumption in
 285 households as provided in Table 5 [75]. Finally, the total emissions from each census area
 286 were allocated to each building in proportion to the TFAs and with consideration of whether
 287 the buildings were collective or detached, and mapped at the level of individual buildings.
 288 Agricultural emissions in this study are defined as emissions from fossil fuel use in
 289 agricultural machinery. The emissions processes were considered as those arising during crop
 290 planting, and those associated emissions were calculated for 62 municipalities in Tokyo as
 291 follows:

$$292 \quad E_{am} = \sum_{i=1}^n \sum_p A_{p,i} \cdot EF_p, \quad (9)$$

293 where E_{am} represents the 2014 total emissions from agricultural machinery use (Gg CO₂); $A_{p,i}$
 294 is the area for crop type p cultivated in municipality i (ha); and EF_p is the annual emission
 295 factor for farmland by crop type (Gg CO₂ ha⁻¹). The $A_{p,i}$ value for each Tokyo municipality
 296 was obtained from the agricultural census [76] and an investigation report on agricultural
 297 products in Tokyo [77], and the EF_p values were from a 2003 report [78] and an academic
 298 paper [79] (Table 6). Farmland was divided into two categories, rice paddy fields and other
 299 farmland, using a land-use map at a 10 × 10 m spatial resolution based on remote-sensing data
 300 for the 2006–2011 period [80]. Finally, the agricultural emissions mapped in each municipality
 301 [65] were sorted into a 10 × 10 m mesh for mapping based on the two types of farmland.
 302

303 **Data integration**

304 Emission calculations and spatial emissions mapping/modeling were integrated using ArcGIS
305 v. 10.4. The world geodetic system (1984) was used for mapping all of the emission sources,
306 and a symbol tool was used here for visualizing the emissions on maps. A 3D map of the
307 emission sources in SG Ward is shown in Fig. 2D as an example, allowing visualization of
308 the emissions from local facilities, road segments, and buildings.

309 All of the data used, their versions or editions, and sources are summarized in Table S4. More
310 than two million building polygons were used to produce emission maps around 500 MB in
311 size. The emission maps were not gridded products since a multi-resolution approach was
312 adopted. The original maps were converted to a 1 km mesh size (Fig. 3) for convenience in
313 data handling.

314

315 **Results and discussion**

316 **Total emissions from the Tokyo Metropolis**

317 Tokyo is one of 47 prefectures in Japan and comprises 23 central city wards and multiple
318 cities, towns, and villages (Table S2). The three highest point-source gridded emissions in
319 2014 occurred in SG, OT, and MN Wards at 6,183, 907, and 253 Gg CO₂ km⁻², respectively
320 (Fig. 3A), due to two large power plants and a major airport being located within these areas.

321 The highest line-source emissions occurred in KT, OT, and EG Wards at 155, 146, and 144
322 Gg CO₂ km⁻², respectively (Fig. 3B). The highest gridded emissions for area sources (Fig.
323 3C) occurred in CD, CO, and SJ Wards at 173, 168, and 164 Gg CO₂ km⁻², respectively.

324 These high emissions are primarily due to the high floor numbers and large building areas for
325 residential, industrial, and commercial use concentrated in these areas. A total emissions map
326 is given in Fig. 3D, with the three highest emissions being 6,210 in SG Ward, 1,058 in OT
327 Ward, and 295 Gg CO₂ km⁻² in MN Ward, respectively.

328 The estimated total 2014 FFCO₂ emissions from Tokyo were 43,916 Gg CO₂ (Table 7),
329 which comprised individual sector contributions of 16,323 from road transportation; 13,085
330 from the industrial and commercial sector; 6,478 from electricity generation; 5,302 from the
331 residential sector; 1,483 from waste incineration; 940 from civil aviation; 279 from
332 waterborne navigation; and 26 Gg CO₂ from the agricultural machine use sector. Total annual
333 emissions from the area, line, and point sources were 18,413, 16,323, and 9,180 Gg CO₂,
334 respectively.

335 The highest point-source emissions (Fig. 4) for 2014 were as follows. Power plants:
336 Shinagawa (3,219), Oi (2,965), and Roppongi energy service (140 Gg CO₂) plants; Civil
337 aviation: Haneda (907), Chofu (15), and Oshima (4 Gg CO₂) airports; Waterborne navigation:
338 Tokyo (253), Mikurajima (5), and Okada (4 Gg CO₂) ports; and waste incineration plants:
339 Tokyo Waterfront Recycle Power (188), Koto new plant (140), and Minato plant (89 Gg
340 CO₂). The data for all 106 point sources are given in Table S1. The 19 power plants
341 contributed 70.6% of the 2014 total point-source emissions (6,478), the 61 waste incineration
342 plants 16.2% (1,483), the 11 airports 10.2% (940), and the 15 ports 3.0% (279 Gg CO₂).
343 The highest line-source emissions for 2014 (Fig. 5) were associated with 30 road segments on
344 two urban highways: Central loop line highway in KS Ward (19.7) and the Coastline
345 highway in KT Ward (18.8 Gg CO₂ km⁻¹). The 2014 emissions from high-speed national

346 highways (total length 150 km) were 1,048 Gg CO₂ (6.4% of the total line-source emissions);
347 urban highways (576 km) 4,867 Gg CO₂ (29.8%); general national highways (726 km) 3,520
348 Gg CO₂ (21.6%); major regional roads (1,625 km) 4,761 Gg CO₂ (29.2%); and general
349 regional roads (1,614 km) 2,128 Gg CO₂ (13.0%).

350 The highest area-source emissions from the industrial and commercial sector for 2014 were
351 recorded in the inner-city areas in CD (172.4), CO (167.0), and SJ (162.0 Gg CO₂ km⁻²)
352 Wards (Fig. 6A), respectively. The industrial and commercial emissions counted from
353 economic census areas were shown in Fig. 6B. Those from the residential sector were in KT
354 (10.0), TS (9.9), and TT (9.5 Gg CO₂ km⁻²) Wards (Fig. 7A), respectively. The residential
355 emissions counted from population census areas were shown in Fig. 7B. Those from the
356 agricultural sector (Fig. 8A) were recorded in MS (0.45) and NK Cities (0.36), and EG Ward
357 (0.33 Gg CO₂ km⁻²), respectively. The agricultural emissions counted for 62 municipalities
358 (Fig. 8B) were finally allocated for high-spatial-resolution map (Fig. 8C).

359

360 **Comparison with other emission estimates made by different approaches**

361 The Tokyo government has reported annual GHG emissions every year since 1990, with
362 emissions being calculated with a top-down approach based on energy consumption [81]. In
363 the governmental EI, emissions for each sector in Tokyo are based on the final energy
364 consumption, including electricity, city gas, liquefied petroleum gas, and kerosene, with
365 emissions being apportioned according to economic indicators, such as family expenditure,
366 commodity values, numbers of vehicles, buildings areas, and passenger and cargo transport in
367 Tokyo.

368 Annual emissions between the present EI and the EI prepared by the Tokyo government are
369 compared for four major categories (Fig. 9A1-2). The governmental EI includes total
370 emissions from the Tokyo Metropolis of 62,120 Gg CO₂ for 2014. The governmental EI
371 includes the following emissions: 29,320 from the industrial and commercial sector; 19,650
372 from the residential sector; 11,570 from transportation; and 1,570 Gg CO₂ from waste
373 incineration. Based on the annual emissions by sector and fuel type in the report [81], we
374 derived the non-electric emissions for the residential sector from the governmental EI as
375 5,532, consistent with our result of 5,302 Gg CO₂. However, those for the industrial and
376 commercial sector are different (governmental EI 6,080, the present EI 13,085 Gg CO₂). For
377 waste incineration, the governmental EI considered only emissions from the fossil-carbon
378 content of waste (1,570), whereas we included both these emissions (1,473) and the
379 combustion agent (10 Gg CO₂).

380 The differences in emissions between the two EIs could be associated mainly with electricity
381 production. This study estimated the emissions from electricity generation as point sources
382 based on fossil-fuel consumption at power plants (direct emissions, Scope-1[6]), while the
383 Tokyo government estimated them based on the final energy consumption (consumption-
384 based emissions, Scope-2 [6]). For example, the government EI includes emissions from
385 electricity consumption by railways and the electricity generated outside the Tokyo area [82].
386 These differences resulted in higher annual emissions from electricity consumption in the
387 government EI (39,460) compared with the EI of the present study (6,478 Gg CO₂).

388 The EAGrid is a reliable EI for multiple pollutants that was developed for the East Asia
389 region in 1995 [83] and revised in 2000 with a focus on local emission sources in Japan

390 (EAGrid-Japan 2000) [84]. In the most recent version (2010), emissions were estimated by
391 adjusting the 2000 emissions according to the increase in national fuel consumption from
392 2000 to 2010 (see Fukui et al. [85]), without any change in the distribution of emission
393 sources. Here we relied on data for the Tokyo domain provided by the developer of EAGrid-
394 Japan 2010 [85].

395 Total emissions in the EAGrid-Japan 2010 EI for Tokyo are 42,009, which is 4.3% lower
396 than our estimate for 2014 (43,916 Gg CO₂). The Tokyo Statistical Yearbook 2015 [86]
397 records increases in population and gross regional product in Tokyo during 2010–2014 of
398 1.7% and 3.9%, respectively. The difference between the two EIs may be related to the
399 change in population and economic growth over the four year period. To compare the two
400 sets of results by source type, the sectoral emissions of the present EI in three categories are
401 summarized in Fig. 9B1 and those for EAGrid are shown in Fig. 9B2. The point-source
402 emissions of EAGrid (5,631 Gg CO₂) include those from power plants, waste incineration
403 plants, vessels, and aircraft; line sources from road transportation (14,672 Gg CO₂); and area
404 sources (21,705 Gg CO₂) from residential and commercial combustion equipment, factory
405 and building boilers, off-road transportation (construction, agricultural, and factory machine
406 use), open burning, and facilities.

407 Spatial distributions of the emissions between the two EIs were compared at a 1 × 1 km
408 resolution by scaling the total EAGrid emissions to our 2014 EI (Fig. 10). The difference in
409 the point sources (Fig. 10A) shows that some gridded emissions of this study were lower than
410 those in EAGrid. To map the gridded values of EAGrid, the counted total emissions from
411 each airport and port were allocated according to the number of persons engaged in the
412 related industry groups (Table S5), with the number of point sources being higher than those
413 in this study. Other differences are due to the EAGrid EI, which does not include recently
414 constructed major sources, such as Shinagawa power plant and Haneda airport domestic
415 terminal 2. As shown in Fig. 11A, the correlation of the gridded emissions of point sources
416 between the two sets of results is very low ($R^2 = 0.42$).

417 Line-source differences (Fig. 10B) vary from -100 to +100 Gg CO₂ km⁻². Differences in
418 emission factors for vehicles and the counting approach for the total travel distance caused
419 the difference in emission estimates. The number of vehicles from the traffic census 2000 and
420 the average travel distance per vehicle were used to estimate the travel distance in EAGrid-
421 Japan 2000 [84], whereas our assessment was based on the road length from the 2015 DRM
422 and the traffic volume from the traffic census 2015. Area-source differences (Fig. 10C) are
423 variable because the EAGrid EI includes residential, industrial, commercial, off-road, open
424 burning, and other emissions as area sources, whereas this study only considers residential,
425 industrial and commercial, and agricultural sectors as area sources. The area-source
426 emissions in the present EI were 3,292 Gg CO₂, lower than those of the EAGrid. As shown in
427 Fig. 11B-C, the correlations of the gridded emissions for line and area sources between the
428 two sets of results are high ($R^2 = 0.74$ for line sources and 0.71 for area sources).

429 Differences in total emissions vary between -700 and +4,500 Gg CO₂ km⁻² (Fig. 10D), with
430 differences being smaller in the western mountain and forest areas and larger in the inner-city
431 areas (eastern Tokyo). As shown in Fig. 11D, the correlation of the total gridded emissions
432 between the two sets of results is moderate ($R^2 = 0.69$). The number of cells in the present EI
433 is much greater than that in EAGrid in the 0–10 Gg CO₂ km⁻² emission range (Fig. 12), with

434 the present EI therefore including more low-emission areas than the EAGrid, while greater
435 10–50 Gg CO₂ km⁻² emissions are included in the latter. The numbers of cells are consistent
436 for the other emission ranges. Thus, we could conclude that even the number of cells in some
437 emission ranges and the total annual emissions between the two sets of results seem to be
438 close but the distributions of the source emissions are different.

439 The Open-source Data Inventory for Anthropogenic CO₂ (ODIAC) [18] provides emissions
440 with less detailed patterns from inner-city areas (eastern Tokyo) to the western mountains and
441 forested areas in Tokyo in 2014 (Fig. 13A). Such characteristic emission distributions are
442 also reported in other urban areas [15, 25, 88]. Differences in gridded annual emissions
443 between our study and ODIAC ranged from about –800 to +3,300 Gg CO₂ cell⁻¹ (Fig. 13B),
444 with differences being greater in inner-city areas. The blue-color grids (Fig. 13B) indicate the
445 three most negative values in densely populated areas. The ODIAC 2014 estimated higher
446 total emissions over these areas, while our estimates were lower. The red-color grids (Fig.
447 13B) indicate the three highest positive values, where two power plants (the Shinagawa and
448 Oi plants, with 3,219 and 2,965 Gg CO₂, respectively) and an international airport (Tokyo
449 Haneda Airport, with 940 Gg CO₂) are located (Table S1). It is clear that ODIAC 2014 does
450 not include such large point sources. We emphasize that local activity data are critical in
451 capturing spatial patterns of local emissions in urban areas.

452

453 **Current limitations and future perspectives**

454 Uncertainties associated with emission factors, activity data, and emission spatial modeling
455 introduce uncertainties in the final emission estimates [e.g., 24, 89]. We refer to the
456 uncertainties on the basis of activity data and emission factors (Table S6) using IPCC
457 guidelines [33, 90]. The total uncertainty is estimated to be ±3.57%, equivalent to 43,916 ±
458 1,568 Gg CO₂.

459 Uncertainties introduced from emissions calculations and mapping processes are likely to be
460 large due to the assumptions and approximations used. For example, the operation ratio of
461 power plants varies with individual plants; however, this study applied averaged utilization
462 efficiency for the whole plants in the calculation process. This approach reduces the
463 variability in emissions at each power plant, leading to poor representation of emissions with
464 higher temporospatial resolution than we applied here. The road segments that are not fully
465 covered by the census contribute over 4,205 km in our calculation. We substituted the
466 average traffic conditions for the road segments to estimate the emissions. This approach
467 could overestimate the traffic quantities and emissions for the segments.

468 In mapping processes, this study treated the mobile emissions of aircraft and vessels as point
469 sources. This means that the whole emissions over their moving paths were aggregated to a
470 point, leading to an overestimate of the point-source emissions. The building emissions were
471 estimated using TFAs of buildings in each census area. In this estimate we used DSM data
472 with a spatial resolution of 30 m, but this spatial resolution is insufficient to calculate the
473 heights and TFAs for individual buildings. Additionally, our downscale approach did not
474 distinguish occupied and vacant houses. All of these limitations should be improved in the
475 next study. As in previous studies (e.g., Hestia [23]), better data availability for emissions
476 calculations and mapping should greatly improve the accuracy of estimates.

477 We plan to update our emission estimates once updated activity data become available. The
478 methods employed here are applicable to other parts of Japan, and the entire country could be
479 covered, although further objective evaluation is necessary. Future work should also include
480 improvements of the methodology for mapping emissions from traffic on narrow roads,
481 modeling of temporal variations (seasonal, weekly, and diurnal), and extending the time
482 period of this study.

483

484 **Conclusions**

485 Spatially explicit estimates of FFCO₂ emissions were prepared for the Tokyo Metropolis,
486 with the EI being primarily compiled using a bottom-up approach. Following the 2006 IPCC
487 guidelines, geolocation data were collected for point, line, and area sources, with the
488 emissions mapped where possible. Detailed activity data, including the utilization efficiency
489 of power plants, load factors of vessels, fossil-carbon contents of waste, and emission factors
490 for fossil-fueled power generation, aircraft movements, navigation, and combustion
491 processes, were utilized to improve the accuracy of emission estimates. The utilization of
492 spatially verified national census data, regional/city specific emission factors, and emission
493 factors for road segments, as well as the consideration of low-emission sectors, such as
494 waterborne navigation and agricultural machinery use, were highlighted. This EI
495 demonstrated that the Tier 3 approach could be applicable not only at a national scale but also
496 a sub-national scale.

497 The total emissions from the Tokyo Metropolis in 2014 were estimated to be 43,916 Gg CO₂.
498 The highest emission sector was road transportation (16,323 Gg CO₂), which accounted for
499 37.2% of the total emissions. Spatial emission patterns were compared with those of EAGrid-
500 Japan and ODIAC, highlighting differences in the distributions of source types. The
501 differences resulted mainly from the counting and mapping approaches used, and the
502 different sector categories.

503 This methodology is applicable to other prefectures and can be used to cover the entire
504 country. This EI facilitates the acquisition of information on emissions from high-emission
505 point sources, buildings, and road segments more than other gridded datasets. It may also be
506 used to validate other EIs and to prepare urban carbon budgets in addition to aiding policy
507 makers in controlling GHG emissions.

508

509 **Abbreviations**

510 CO₂: carbon dioxide

511 FFCO₂: carbon dioxide emissions from fossil fuel combustion

512 EI: emission inventory

513 GPC: Global Protocol for Community-Scale Greenhouse Gas Emission Inventories

514 UNFCCC: UN Framework Convention on Climate Change

515 IPCC: Intergovernmental Panel on Climate Change

516 GHG: greenhouse gas
517 PB: purely geographic-based
518 EAGrid-Japan: East Asian Air Pollutant Emission Grid Database for Japan
519 ODIAC: Open-source Data Inventory for Anthropogenic CO₂
520 MW: megawatt
521 LTO: landing and take-off
522 ICAO: International Civil Aviation Organization
523 GT: gross tonnage
524 MSW: municipal solid waste
525 CA: combustion agent
526 DRM: digital road map
527 GIS: geographic information system
528 TFA: total floor area
529 DSM: digital surface model
530 DEM: digital elevation model

531

532 **Declarations**

533 **Ethics approval and consent to participate**

534 Not applicable.

535 **Consent for publication**

536 Not applicable.

537 **Availability of data and materials**

538 The data used in this study are either presented in this manuscript or available from the data
539 source indicated. The authors plan to make the data product developed in this study publicly
540 available with a DOI.

541 **Competing interests**

542 The authors declare that they have no competing interests.

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546 **Authors' contributions**

547 RC carried out the data collection and analysis with support from MS. TF provided the EAGrid-
548 Japan2010 emission inventory and guidance on the use of the inventory in the data analysis.
549 RC wrote the manuscript with input from MS. RC and AI provided critical comments that
550 shaped the study and manuscript. All the authors contributed to the final version of the
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838

839 **Figure captions**

840 **Fig. 1.** Conceptual framework for emission mapping.

841

842 **Fig. 2.** Examples of vector maps for emission sources in SG Ward, Tokyo. (A) Locations of
 843 point emission sources. (B) Road segments for line sources. (C) Building polygons for area
 844 sources (blue line shows the boundary of the area). (D) 3D emission map for all sources (Gg
 845 CO₂ yr⁻¹ per road segment for road emissions and Gg CO₂ yr⁻¹ per polygon for others).

846

847 **Fig. 3.** Emission maps with 1 × 1 km mesh for (A) point sources, (B) line sources, (C) area
 848 sources, and (D) all sources. Unit: Gg CO₂ km⁻² yr⁻¹.

849

850 **Fig. 4.** Map of 106 point sources in Tokyo (areas in blue frames indicate islands). The point
 851 in cyan indicates the highest emissions at Shinagawa power plant (3,219 Gg CO₂ yr⁻¹).

852

853 **Fig. 5.** Map of emissions from line sources for each road segment. The 30 road segments
 854 with the highest emissions are marked in black. Unit: Gg CO₂ km⁻¹ yr⁻¹.

855

856 **Fig. 6.** Map of emissions from the industrial and commercial sector with (A) 1 × 1 km mesh,
 857 unit: Gg CO₂ km⁻² yr⁻¹; (B) 5,318 economic census areas, unit: Gg CO₂ yr⁻¹. The municipality
 858 boundary for the area with the highest annual emissions (up to 82.2 Gg CO₂) is marked in cyan.

859

860 **Fig. 7.** Map of emissions from the residential sector with (A) 1 × 1 km mesh, unit: Gg CO₂
 861 km⁻² yr⁻¹; (B) 5,578 population census areas, unit: Gg CO₂ yr⁻¹. The municipality boundary
 862 for the area with the highest annual emissions (up to 6.6 Gg CO₂) is marked in cyan.

863

864 **Fig. 8.** Maps of emissions from the agricultural machine use sector with (A) 1×1 km mesh,
865 unit: $\text{Mg CO}_2 \text{ km}^{-2} \text{ yr}^{-1}$. (B) 62 municipalities, unit: $\text{Mg CO}_2 \text{ yr}^{-1}$. The area with the highest
866 annual emissions ($2,765 \text{ Mg CO}_2 \text{ yr}^{-1}$) is marked in cyan. (C) high-spatial-resolution map on
867 a grid with cell size of 10×10 m, unit: $\text{Kg CO}_2 \text{ yr}^{-1}$ per cell.

868

869 **Fig. 9.** Comparisons on annual CO_2 emissions in Tokyo between the present EI (A-1) and
870 Tokyo government 2014 EI (A-2), and between the present EI (B-1) and EAGrid-Japan 2010
871 (B-2). Unit: Gg CO_2 .

872 Note: In A-1, the industrial and commercial category includes emissions from the industrial and
873 commercial sector and the electricity generation sector. The transportation category includes
874 emissions from the road transportation, civil aviation, and waterborne navigation sectors.

875 In A-2, the transportation category includes emissions from the railway, road transportation, civil
876 aviation, and waterborne navigation sectors.

877 In B-2, point sources include power plants, waste incineration plants, vessels, and aircrafts. Line
878 sources refer to road transportation. Area sources include residential and commercial combustion
879 equipment, factory and building boilers, off-road transportation, open burning, and facilities without
880 identified locations.

881

882 **Fig. 10.** Differences in emissions between the present EI and 2010 EAGrid-Japan EI at a
883 resolution of 1×1 km for: (A) point sources, (B) line sources, (C) area sources, and (D) all
884 sources. Unit: $\text{Gg CO}_2 \text{ km}^{-2} \text{ yr}^{-1}$. (Difference = emissions from the present EI – 2010
885 EAGrid-Japan EI, after adjustment of EAGrid emissions, as described in the text.).

886

887 **Fig. 11.** Scatter plots of gridded emissions by source types between the present EI and
888 EAGrid for: (A) point sources, (B) line sources, (C) area sources, and (D) all sources. Unit:
889 $\log_{10} \text{Gg CO}_2 \text{ km}^{-2} \text{ yr}^{-1}$.

890

891 **Fig. 12.** Frequency distribution of gridded emissions ($\text{Gg CO}_2 \text{ km}^{-2} \text{ yr}^{-1}$) for this study
892 (green) and EAGrid-Japan 2010 adjusted (blue). $n = 2,688$.

893

894 **Fig. 13.** Emission maps with a 30×30 arcsec mesh size for (A) ODIAC 2014 clipped for the
895 Tokyo domain, (B) gridded emission differences between this study and ODIAC 2014
896 clipped for the Tokyo domain (Difference = emissions from the present EI minus ODIAC
897 2014). Unit: $\text{Gg CO}_2 \text{ yr}^{-1} \text{ cell}^{-1}$.

898

899 **Table captions**

900 **Table 1** The differences on high resolution CO_2 emission estimates by bottom-up approach
901 between this study and previous studies

902

903 **Table 2** Spatial data used for identifying CO_2 emission sources, and other data used for
904 counting emissions for each sector in Tokyo. Note that several sectors are not consistent with
905 the IPCC definitions. For example, (1) only the LTO cycle emissions were used here for civil
906 aviation, whereas the IPCC sector includes emissions from LTO cycle and cruise; (2) only

907 passenger and cargo ships with round trips to the ports were considered here for the
908 waterborne navigation sector, whereas the IPCC sector covers all water-borne transport, from
909 recreational craft to large ocean-going cargo ships; and (3) two IPCC sectors (manufacturing
910 and commercial sectors) were combined to form the industrial and commercial sector.

911

912 **Table 3** CO₂ emission factors for vehicles by vehicle type and speed (2010), extracted from
913 experimental results [66].

914

915 **Table 4** Annual consumption of fossil fuels, worker numbers, and CO₂ emission factors for
916 workers by category in Tokyo, derived from the 2014 economic census [69] and the energy-
917 balance table for Tokyo (2014) [70].

918

919 **Table 5** CO₂ emission factors for households by occupancy and building type, based on an
920 investigation of residential energy consumption [75].

921

922 **Table 6** CO₂ emission factors for farmland by crop type [78, 79].

923

924 **Table 7** Estimates of annual CO₂ emissions from Tokyo (2014) by sector and source type.

925

926 **Additional file 1**

927 **Table S1** Ownership, facility description, location, and emissions for 106 point-type emission
928 sources (2014). Note: * indicates that the average utilization rate of CAs (2014) from these facilities
929 was extended to all of the waste incineration plants.

930 **Table S2** Municipality names, abbreviations, areas, populations, and emissions for the 62
931 Tokyo municipalities (2014).

932 **Table S3** Parameter settings for the calculation of emissions from vessels [55, 56].

933 Note: GT classes #A: 5–10 t, 10–15 t, 15–20 t, 150–200 t, 350–500 t, 500–1,000 t; #B: 1–70 t,
934 70–500 t, 500–3,000 t; #C: <500 t, 500–1,000 t, 1,000–3,000 t, 3,000–6,000 t, 6,000–10,000 t,
935 10,000–30,000 t, 30,000–60,000 t, 60,000–100,000 t, >100,000 t; #D: <500 t, 500–5,000 t,
936 5,000–10,000 t, >10,000 t.

937 **Table S4** Components of this study and relevant data sources.

938 **Table S5** Differences in emission counting and mapping by source type between EAGrid-
939 Japan and this study.

940 **Table S6** Uncertainties from activity data and emission factors, by sector.