1 # The Hestia Fossil Fuel CO₂ Emissions Data Product for the Los
2 # Angeles Megacity (Hestia-LA)

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14 **Abstract**. As a critical constraint to atmospheric CO_2 inversion studies, bottom-up spatiotemporally-explicit

15 emissions data products are necessary to construct comprehensive CO_2 emission information systems useful for

16 trend detection and emissions verification. High-resolution bottom-up estimation is also useful as a guide to

17 mitigation options, offering details that can increase mitigation efficiency and synergize with other policy goals at

18 the national to sub-urban spatial scale. The 'Hestia Project' is an effort to provide bottom-up fossil fuel ($FFCO_2$)

19 emissions at the urban scale with building/street and hourly space-time resolution. Here, we report on the latest

20 urban area for which a Hestia estimate has been completed – the Los Angeles Megacity, encompassing five

21 counties: Los Angeles County, Orange County, Riverside County, San Bernardino County and Ventura County. We

22 provide a complete description of the methods used to build the Hestia $FFCO_2$ emissions data product which is

23 presented on a 1 km x 1 km grid for the years 2010-2015. We find that the LA Basin emits 48.06 ($\pm$ 5.3) MtC/yr,

24 dominated by the onroad sector. Because of the uneven spatial distribution of emissions, 10% of the largest emitting

25 gridcells account for 93.6%, 73.4%, 66.2%, and 45.3% of the industrial, commercial, onroad, and residential sector

26 emissions, respectively. Hestia $FFCO_2$ emissions are 10.7% larger than the inventory estimate generated by the local

27 metropolitan planning agency, a difference that is driven by the industrial and electricity production sectors. The

28 Hestia-LA v2.5 emissions data product can be downloaded from the data repository at the National Institute of

29 Standards and Technology (https://doi.org/10.18434/T4/1502503).

30 **1 Introduction**

31 Driven by the growth of fossil fuel combustion, the amount of carbon dioxide (CO_2), the most important

32 anthropogenic greenhouse gas (GHG) in the Earth's atmosphere, recently reached an annual average global mean

33 concentration of 402.8 ± 0.1 parts per million (ppm) on its way to doubling pre-industrial levels (IPCC, 2013;

34 LeQuere et al., 2018). We have also witnessed the first time that the majority of world's inhabitants reside in urban

35 areas. This trend, like atmospheric CO_2 levels, is intensifying. Projections show cities worldwide could add 2 to 3

36 billion people this century and are projected to triple in area by 2030 (UN DESA 1015; Seto et al., 2012).

These two thresholds are linked—almost three-quarters of energy-related, atmospheric CO_2 emissions are driven by urban activity (Seto et al., 2014). If the world's top 50 emitting cities were counted as one country, that nation would rank third in emissions behind China and the United States (World Bank 2010). Indeed, urbanization is a factor shaping national contributions to internationally agreed emission reductions, as subnational governments are playing an increasing role in climate mitigation and adaptation policy implementation (Bulkeley 2010; Hsu et al., 2017). Furthermore, the pace of urbanization continues to increase and opportunities to avoid carbon "lock-in" - where relationships between technology, infrastructure, and urban form dictate decades of high-CO_2 development - are diminishing (Ürge-Vorsatz et al., 2018; Seto et al., 2016; Erickson et al., 2015).

Motivated by these numerical realities and the recognition that low-emission development is consistent with a variety of other co-benefits (e.g. air quality improvement), cities are taking steps to mitigate their CO_2 emissions (Rosenzweig et al., 2010; Hsu et al., 2015; Watts 2017). For example, 9120 cities representing over 770 million people (10.5% of global population) have committed to the Global Covenant of Mayors (GCoM) to promote and support action to combat climate change (GCoM, 2018). Over 90 large cities, as part of the C40 network, have similarly committed to mitigation actions with demonstrable progress. However, the scale of actual reductions remains modest, despite the many pledges and initial progress. For example, a recent study reviewed 228 cities pledged to reduce 454 megatons of CO_2 per year by 2020 (Erickson and Lazarus, 2012). Were they to meet these commitments, the reduction would account for about 3% of current global urban emissions and less than 1% of total global emissions projected for 2020. More important, there is a need for timely information to manage and assess the performance of implemented mitigation efforts and policies (Bellassen et al., 2015).

One of the barriers to targeting a deeper list of emission reduction activities is the limited amount of actionable emissions information at scales where human activity occurs: individual buildings, vehicles, parks, factories and power plants (Gurney et al., 2015). These are the scales at which interventions in CO_2-emitting activity must occur. Hence, the emissions magnitude and driving forces of those emissions must be understood and quantified at the "human" scale to make efficient (i.e. prioritizing the largest available emitting activities/locales) mitigation choices and to capture the urban co-benefits that also occur at this scale (e.g. improve traffic congestion, walkability, green space). Similarly, a key obstacle to assessing progress is a lack of independent atmospheric evaluation (ideally consistent in space and time with the human-scale emissions mapping) (Duren and Miller 2011).

Existing methods and tools to account for urban emissions have been developed primarily in the non-profit community (WRI/WBCSD, 2004; Fong et al., 2014). In spite of these important efforts, most cities lack independent, comprehensive and comparable sources of data and information to drive and/or adjust these frameworks. Furthermore, the existing tools and methods are designed at an aggregate level (i.e. whole city, whole province), missing the most important scale—sub-city—and hence provide limited actionable information.

The scientific community has begun to build information systems aimed at providing independent assessment of urban CO_2 emissions. Through a combination of atmospheric measurements, atmospheric transport modeling and data-driven "bottom-up" estimation, the scientific community is exploring different methodologies, applications, and uncertainty estimation of these approaches (Hutyra et al., 2014). Atmospheric monitoring includes ground-based CO_2 concentration measurements (McKain et al., 2012; Djuricin et al., 2010; Miles et al., 2017; Turnbull et al.,

74   2015, Verhulst et al., 2017), ground-based eddy flux measurements (Christen 2014; Crawford and Christen 2014;

75   Grimmond et al., 2002; Menzer et al., 2015; Velasco and Roth 2010; Velasco et al., 2005), aircraft-based flux

76   measurements (Mays et al., 2009; Cambaliza et al., 2014; 2015) and whole-column abundances from both ground,

77   and space-based, remote sensing platforms (Wunch et al., 2009; Kort et al., 2012; Wong et al., 2015; Schwandner et

78   al., 2018).

79   "Bottom-up" approaches, by contrast, include a mixture of direct flux measurement, indirect measurement and

80   modeling. Common among the bottom-up approaches are those that include flux estimation based on a combination

81   of activity data (population, number of vehicles, building floor area) and emission factors (amount of CO_2 emitted

82   per activity), socioeconomic regression modeling, or scaling from aggregate fuel consumption (VandeWeghe and

83   Kennedy, 2007; Shu and Lam, 2011; Zhou and Gurney, 2011; Gurney et al., 2012; Jones and Kammen, 2014;

84   Ramaswami and Chavez, 2013; Patarasuk et al., 2016; Porse et al., 2016). Direct end-of-pipe flux monitoring is

85   often used for large point sources such as power plants (Gurney et al., 2016). Indirect fluxes (those occurring outside

86   of the domain of interest but driven by activity within) can be estimated through either direct atmospheric

87   measurement (and apportioned to the domain of interest) or can be modeled through process-based (Clark and

88   Chester 2017) or economic input-output models (Ramaswami et al., 2008).

89   Integration of bottom-up urban flux estimation with atmospheric monitoring has been achieved with atmospheric

90   inverse modeling, an approach whereby surface fluxes are estimated from a best fit between bottom-up estimation

91   and fluxes inferred, via atmospheric transport modeling, from atmospheric concentrations (Lauvaux et al., 2013;

92   Lauvuax et al., 2016; Breon et al., 2015; Davis et al., 2017). Though the various measurement and modeling

93   components continue to be tested, integration offers an urban anthropogenic CO_2 information system which can

94   provide accuracy, emissions process information, and spatiotemporal detail. This combination of attributes satisfies

95   a number of urgent requirements. For example, it can offer the means to evaluate urban emissions mitigation efforts

96   by assessing urban trends. Space, time, and process detail of emitting activity can guide mitigation efforts,

97   illuminating where efficient opportunities exist to maximize reductions or focus new efforts. Finally, emissions

98   quantification is also seen as a potentially powerful metric with which to better understand the urbanization process

99   itself, given the importance of energy consumption to the evolution of cities.

100   The Hestia Project was begun to estimate bottom-up urban fossil fuel CO_2 ($FFCO_2$) fluxes for use within integrated

101   flux information systems. Begun in the city of Indianapolis, the Hestia effort is now part of a larger experiment that

102   includes many of the modeling and measurement aspects described above. Referred to as the Indianapolis Flux

103   Experiment (INFLUX), this integrated effort has emerged to test and explore quantification and uncertainties of the

104   urban CO_2 and CH_4 measurement and modeling approaches using Indianapolis as the testbed experimental

105   environment (Whetstone et al., 2018; Davis et al., 2017).

106   Because urban areas differ in key attributes such as size, geography, and emission sector composition, multiple cities

107   are now being used to test aspects of anthropogenic CO_2 monitoring and modeling. The Hestia approach has been

108   used in a number of these urban domains. Here, we provide the methods and results from one of those urban domains,

109   the Los Angeles Basin Megacity. The Hestia-LA effort was developed under the Megacities Carbon framework

110   (https://megacities.jpl.nasa.gov/portal/). It was designed to serve the Megacities Carbon Project in a similar capacity

111   to its role in INFLUX. The Hestia-LA result is unique in that it is the first high-resolution spatiotemporally-explicit
112   inventory of FFCO$_2$ emissions centered over a megacity. A preliminary version of Hestia-LA containing only the
113   transportation sector emissions was reported by Rao et al. (2017). While emphasis thus far has been focused on
114   atmospheric CH$_4$ monitoring analyses in the LA megacity (Carranza et al., 2017; Wong et al., 2016; Verhulst et al.,
115   2017; Hopkins et al., 2016), work is ongoing to use the extensive atmospheric CO$_2$ observing capacity in the Los
116   Angeles domain (e.g. Newman et al., 2016; Feng et al., 2016; Wong et al., 2015; Wunch et al., 2009) within an
117   atmospheric CO$_2$ inversion.

118   In this paper, we describe the study domain, the input data, uncertainty, and the methods used to generate the Hestia-
119   LA (v2.5) data product and provide descriptive statistics at various scales of aggregation. We compare the Hestia
120   results to the metro region planning authority estimate and place the results in the context of urban greenhouse gas
121   mitigation. We discuss known gaps and weaknesses in the approach and goals for future work.

122   **2 Methods**

123   **2.1 Study Domain**

124   The Los Angeles metropolitan area is the second-largest metropolitan area in the United States and one of the largest
125   metropolitan areas in the world. Under the definition of the Metropolitan Statistical Area (MSA) by the U.S. Office
126   of Management and Budget, Metropolitan Los Angeles consists of Los Angeles and Orange counties with a land
127   area of 12,562 km^2 and a population of 9,819,000. The Greater Los Angeles Area, as a Combined Statistical Area
128   (CSA) defined by the U.S. Census Bureau, encompasses the three additional counties of Ventura, Riverside, and San
129   Bernardino with a total land area of 87,945 km^2 and an estimated population of 18,550,288 in 2014. The Hestia-LA
130   FFCO$_2$ emissions data product covers the complete geographic extent of these five counties including the Eastern,
131   relatively non-urbanized portions of San Bernardino and Riverside counties. Airport emissions associated with
132   aircraft up to 3000 feet are included as are marine shipping emissions out to 12 nautical miles from the coastal
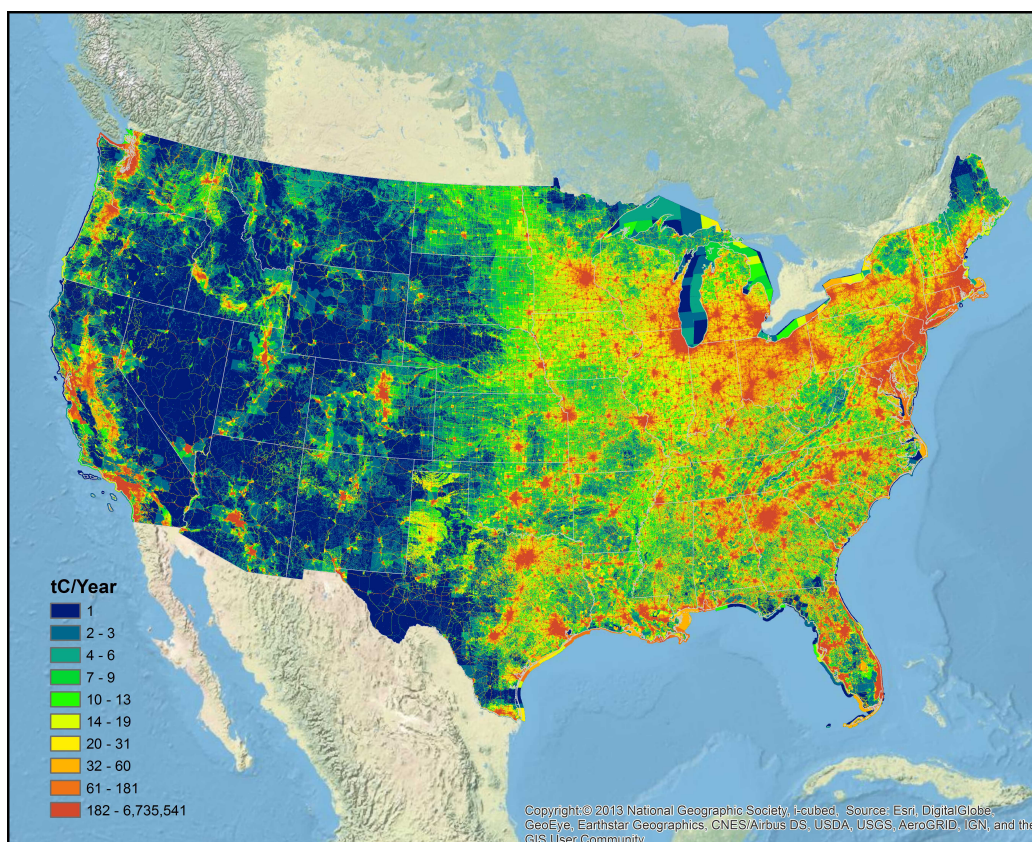133   boundary.

134

Figure 1: The Hestia-LA urban domain

135

136 **2.2 Input data**

137 Input data to the Hestia-LA data product are supplied by output of the Vulcan Project (Figure 2), a quantification of

138 FFCO$_2$ emissions at fine space and time scales for the entire US landscape (Gurney et al., 2009) The Hestia-LA

139 process extracts these results for the five counties within the Hestia-LA domain and adjusts these estimates where

140 superior local data are available and further downscales/distributes the Vulcan v3.0 results to buildings and street

141 segments. Details of the Vulcan v3.0 methodology is provided elsewhere (Gurney et al., 2018). Here, we summarize

142 the Vulcan v3.0 methods and then provide greater detail regarding the Hestia-LA processing of that data to high-

143 resolution space/time scales.

144

Figure 2: Total annual FFCO$_2$ emissions for the year 2011 from the Vulcan v3.0 output.

146 The Vulcan v3.0 input data (the output of which is the input for the Hestia-LA) are organized following nine

147 economic sector divisions (see Table 1) - residential, commercial, industrial, electricity production, onroad, nonroad,

148 railroad, commercial marine vessel, and airport. Also included are emissions associated with the calcining process in

149 the production of cement. The data sources within each sector are either acquired as FFCO$_2$ emissions (the onroad

150 sector and most of the nonroad and electricity production sectors) or as carbon monoxide (CO) emissions (all other

151 sectors) and transformed to FFCO$_2$ emissions via emission factors. Furthermore, the data sources are represented

152 geographically as either geocoded emitting locations ("point") or as spatial aggregates ("nonpoint" or area-based

153 emissions). Point sources are stationary emitting entities identified to a geocoded location such as industrial facilities

154 in which emissions exit through a stack or identifiable exhaust feature (USEPA, 2015a). Area or nonpoint source

155 emissions are not inventoried at the facility-level but represent diffuse emissions within an individual U.S. county.

156 Because the focus of the current study is CO$_2$ emissions resulting from the combustion of a fossil fuels, fugitive or

157 evaporative emissions are not included nor are "process" emissions, for example, associated with high-temperature

158 metallurgical processes.

159 Much of the input data for Vulcan v3.0 are acquired from the Environmental Protection Agency's (EPA) National

160 Emission Inventory (NEI) for the year 2011 (referred to hereafter as the "2011 NEI") which is a comprehensive

161 inventory of all criteria air pollutants (CAPs) and hazardous air pollutants (HAPs) across the United States (USEPA,

162 2015b). All of the individual record-level reporting in the 2011 NEI comes with a source classification code (SCC)

163 which codifies the general emission technology, fuel type used, and sector (*USEPA* 1995).

164 FFCO$_2$ emissions from the electricity production sector are primarily retrieved from two sources other than the 2011

165 NEI. The first is the EPA's Clean Air Markets Division (CAMD) data (USEPA, 2015c) which reports FFCO$_2$

166 emissions at geocoded electricity production facility locations. The second is the Department of Energy's Energy

167 Information Administration (DOE EIA) reporting data (DOE/EIA, 2003) which reports fuel consumption at

168 geocoded electricity production facility locations. Some electricity production emissions are retrieved from the 2011

169 NEI (as CO emissions). Overlap between these three data sources is eliminated via preference in the order listed

170 above. A detailed comparison made between the CAMD and EIA FFCO$_2$ emissions along with greater detail

171 regarding data sources, data processing and procedures can be found in Quick et al., (2014) and Gurney et al. (2014;

172 2016; 2018).

173 The 2011 onroad FFCO$_2$ emissions are retrieved from the EMissions FACtors 2014 model (EMFAC2014), produced

174 by the California Air Resources Board (CARB 2014). Onroad transportation represents all mobile transport using

175 paved roadways and include both private and commercial vehicles of many individual classes (e.g., passenger

176 vehicles, buses, light duty trucks, etc). The nonroad sector, by contrast, includes all surface mobile vehicles that do

177 not travel on designated paved roads surface and include a large class of vehicles such as construction equipment

178 (e.g., bulldozers, backhoes, etc.), ATVs, snowmobiles, and airport fueling vehicles. The nonroad emissions are

179 derived from the 2011 NEI reporting of nonroad CO emissions. Airport emissions include all the emissions

180 emanating from aircraft during their taxi, takeoff, landing cycles up to 3000 feet and are derived from the 2011 NEI

181 point reporting. Other activities occurring at airports resulting in FFCO$_2$ emissions are captured in the commercial

182 building sector (building heating) or the nonroad sector (baggage vehicles), sourced to the 2011 NEI nonpoint, 2011

183 NEI point and 2011 NEI nonroad reporting. Railroad emissions include passenger and freight rail travel and are

184 sourced to the 2011 NEI nonpoint and point reporting. Commercial marine vessels (CMV) include all commercial-

185 based aquatic vessels on either ocean or freshwater sourced to the 2011 NEI nonpoint reporting. Personal aquatic

186 vehicles such as pleasure craft and sailboats are included in the nonroad sector. Emissions associated with cement

187 calcining are included given its potential size and the tradition of including it with CO$_2$ inventories and use

188 information from multiple sources (PCA, 2006; USGS, 2003; IPCC, 2006).

189 The FFCO$_2$ emissions input to the Hestia system from the Vulcan v3.0 output is associated with spatial elements

190 represented by points, lines and polygons, depending upon the data source, the sector and the available spatial proxy

191 data (Table 1). Further spatialization and temporalization occurs in the Hestia system.

192 **Table 1. Data sources used in the spatiotemporal distribution of FFCO$_2$ emissions (text provides acronym**
193 **explanations and sources).**

Sector/type	Emissions Data Source	Original spatial resolution/information	Spatial distribution	Temporal distribution
Onroad	EMFAC[a], EPA NEI[b] onroad	County, road class, vehicle class	SCAG AADT[c]	PeMS[d], CCS[e]
Electricity production	CAMD[f] CO2, EIA[g] fuel, EPA NEI point CO	Lat/lon, fuel type, technology	EPA NEI Lat/Lon, Google Earth	CAMD, EIA and EPA

Residential nonpoint buildings	EPA NEI nonpoint CO	County, fuel type	SCAG Parcel, floor area, DOE RECS NE-EUI[h], LA County building footprint	eQUEST[i]
Nonroad	NEI nonpoint CO	County, vehicle class	EPA spatial surrogates (vehicle class specific)	EPA temporal surrogates (by SCC[j])
Airport	EPA NEI point CO	Lat/lon, aircraft class	Lat/Lon	LAWA[k]
Commercial nonpoint buildings	EPA NEI nonpoint CO	County, fuel	SCAG Parcel, floor area, DOE CBECS NE-EUI[l]	eQUEST
Commercial point sources	EPA NEI point CO	Lat/lon, fuel type, combustion technology	EPA NEI Lat/Lon, Google Earth	eQUEST
Industrial point sources	EPA NEI point CO	Lat/lon, fuel type, combustion technology	EPA NEI Lat/Lon, Google Earth	EPA temporal surrogates (by SCC)
Industrial nonpoint buildings	EPA NEI nonpoint CO	County, fuel type	SCAG-Parcel, floor area, DOE MECS NE-EUI[m]	eQUEST
Commercial Marine Vessels	EPA NEI nonpoint CO	County, fuel type, port/underway	MEM[n]	MEM
Railroad	EPA NEI nonpoint CO, EPA NEI point CO	County, fuel type, segment	EPA NEI rail shapefile and density distribution	EPA temporal surrogates (by SCC)

194   a. Emissions Factors Model
195   b. Environmental Protection Agency, National Emissions Inventory
196   c. Southern California Association of Governments, Annual Average Daily Traffic
197   d. Performance Measurement System
198   e. Continuous Count Stations
199   f. Clean Air Markets Division
200   g. Energy Information Administration
201   h. Department of Energy Residential Energy Consumption Survey, non-electric energy use intensity
202   i. Quick Energy Simulation Tool
203   j. Source Classification Code
204   k. Los Angeles World Airport
205   l. Department of Energy Commercial Energy Consumption Survey, non-electric energy use intensity
206   m. Department of Energy Manufacturing Energy Consumption Survey, non-electric energy use intensity
207   n. Marine Emissions Model

208   To estimate FFCO$_2$ emissions as a multiyear time series from 2010 to 2015, the results for the year 2011 were scaled

209   using sector/state/fuel consumption data (thermal units) from the DOE EIA (DOE/EIA, 2018). The electricity

210   production sector was an exception to this approach where year-specific data was available in the CAMD and EIA

211   data sources. Ratios were constructed relative to the year 2011 in all SEDS sector designations for each US state.

212   The ratio values are applied to the annual totals in each of the sector/fuel categories specific to the state FIPS code.

213   **2.3 Space/time processing**

214   **2.3.1 Residential, commercial, industrial nonpoint buildings**

215   The general approach to spatializing the residential, commercial and industrial nonpoint FFCO$_2$ emissions is to

216   allocate the county-scale, fuel-specific annual sector totals to individual buildings (or parcels) using data on building

217   type, building age, total floor area, energy use intensity, and location.

218   A portion of the Hestia-LA building information were provided by the Southern California Association of

219   Governments (SCAG) (SCAG, 2012) and included building type, age, floor area, and location. The spatial

220   resolution of this information was at the land parcel scale (larger than the building footprint). Building footprint data

221   was available in the county of Los Angeles only which offered additional building floor area information needed to

222   correct some floor area values in the SCAG parcel data (LAC, 2016). For example, a large number of commercial

223   parcels with zero floor area were found in the Riverside County data which were visually inspected in Google Earth

224   to contain qualifying buildings. These floor area values were corrected through the combination of the Census

225   block-group General Building Stock (GBS) database from the Federal Emergency Management Agency (FEMA)

226   (FEMA, 2017) and the National Land Cover Database 2011 (NLCD) which classifies the US land surface in 30m

227   pixels (Homer et al., 2015).

228   Building energy use intensity was derived from data gathered by the DOE EIA and the California Energy

229   Commission (CEC). The DOE EIA Commercial Buildings Energy Consumption Survey (CBECS), Manufacturing

230   Energy Consumption Survey (MECS), and Residential Energy Consumption Survey (RECS) represent regional

231   surveys of building energy consumption categorized by building type, fuel type, and age cohort (RECS, 2013;

232   CBECS, 2016; MECS, 2010). Data for the Pacific West Census Division was used and in the case of the commercial

233   sector, was appended by the CECs Commercial End-Use Survey (CEUS) data (CEC, 2006).

234   In the residential sector the non-electric energy use intensity (NE-EUI) was calculated from the reported energy

235   consumed and total floor area sampled specific to five building types (Table 2) in the 2009 RECS survey. This was

236   additionally categorized by fuel type (natural gas and fuel oil) and two age cohorts (pre-1980, post-1979).

237   **Table 2. Residential NE-EUI survey values by building type from the Residential Energy Consumption**
238   **Survey (RECS)**

RECS building type	Pre-1980 NG NE-EUI (kbtu/ft²)	Post-1979 NG NE-EUI (kbtu/ft²)	Pre-1980 Fuel oil NE-EUI (kbtu/ft²)	Post-1979 Fuel oil NE-EUI (kbtu/ft²)
Mobile home	52.56	22.90	NA*	NA
Single-family detached house	24.53	18.00	18.87	7.23
Single-family attached house	42.56	32.38	NA	NA
Apartment building with 2-4 units	27.84	42.27	NA	NA
Apartment building with 5 or more units	17.21	30.85	NA	NA

239   * "NA" – not applicable. This indicates that there was no fuel consumption of this type evident from the survey data.

240   In the commercial sector, the NE-EUI was similarly calculated from the 2012 CBECS energy consumption

241   microdata and total floor area sampled specific to twenty building types, two fuel types (natural gas and fuel oil) and

242   two age cohorts (pre-1980 and post-1979). However, the sampling for the two age cohorts was insufficient to

243   generate estimates and the age distinction was eliminated. Furthermore, where the sample sizes remained small, NE-

244   EUI data from the CEUS was used in place of CBECS estimates (7 of 20 building types qualified). As the CEUS

245   follows a building typology different from CBECS, a crosswalk of building types between the two datasets was

246   necessary (Table 3).

247   **Table 3. Building type crosswalk and NE-EUI values for commercial buildings derived from the CBECS and**
248   **CUES databases**

CBECS building class	CUES building class	NG NE-EUI (kbtu/ft²)	Fuel oil NE-EUI (kbtu/ft²)
Vacant	Miscellaneous	9.3	2.5
Office	All Offices	17.9*	1.67
Laboratory	Miscellaneous	174.7	0.93
Nonrefrigerated warehouse	Unrefrigerated Warehouse	3.1*	1.03
Food sales	Food Store	27.6*	2.5
Public order and safety	Miscellaneous	58.2	2.09
Outpatient health care	Health	29.1	3.05
Refrigerated warehouse	Refrigerated Warehouse	5.6*	2.5
Religious worship	Miscellaneous	35.7	0.00
Public assembly	Miscellaneous	26.5	0.23
Education	College, School	25.1*	1.7
Food service	Restaurant	210*	100.5
Inpatient health care	Health	113.9	2.6

Nursing	Health	67.4	1.2
Lodging	Lodging	42.4*	1.4
Strip shopping mall	Retail	62.7	2.5
Enclosed mall	Retail	4.8	0.02
Retail other than mall	Retail	13.6	16.7
Service	Miscellaneous	34.2	0.45
Other	Miscellaneous	18.5	5.3

249   * NE-EUI uses the CUES NE-EUI value due to sampling limitations in the CBECS data.

250   Unlike the commercial and residential survey data, the 2010 MECS survey data does not quantify energy

251   consumption for individually sampled buildings but rather reports the sum of the sampled buildings within each

252   census region categorized by manufacturing sector. The resulting NE-EUI values are shown in in Table 4. Like the

253   commercial data, there was inadequate sampling to justify two age cohorts.

254   **Table 4. Industrial NE-EUI survey values from the DOE EIA MECS database**

MECS Class	NG NE-EUI (kbtu/ft^2)	Fuel oil NE-EUI (kbtu/ft^2)
Food	519.3	30.5
Beverage and Tobacco Products	162.4	8.5
Textile Mills	144.9	9.3
Textile Product Mills	63.4	0
Apparel	35.1	0
Leather and Allied Products	66.7	0
Wood Products	76.6	49.5
Paper	672.8	69.1
Printing and Related Support	96.6	0
Petroleum and Coal Products	9766.0	436.2
Chemicals	2126.3	17.9
Plastics and Rubber Products	124.7	2.4
Nonmetallic Mineral Products	556.0	48.9
Primary Metals	895.0	16.7
Fabricated Metal Products	124.2	2.3
Machinery	78.6	3.3
Computer and Electronic Products	80.0	0
Electrical Equip., Appliances, and Components	133.3	3.7
Transportation Equipment	100.6	4.0
Furniture and Related Products	28.6	0
Miscellaneous	44.7	2.8

255   The NE-EUI values derived from the CBECS/RECS/MECS and CEUS survey data reflect the total building fuel

256   consumption for a specific fuel in a census region divided by the total floor area of all buildings in that census region

257   consuming that fuel. This generates a mean building NE-EUI value. Actual buildings will vary around that mean

258   value for a variety of reasons including different occupancy schedules, different energy efficiencies (in the envelope

259   or heating/cooling system), different microclimate, and other physical/behavioral characteristics. Furthermore, the

260   NE-EUI value applied in this way will not capture the reality that some buildings do not use fossil fuel (electricity-

261   only buildings) or that some buildings use one fossil fuel only versus another or use a mix of fuels in a proportion

262   different from the county total. Hence, each building will be allocated a mix of fossil fuel consumption identical to

263   the county total.

264 **2.3.1.1 Spatial distribution**

265 The county-scale commercial, residential and industrial nonpoint FFCO$_2$ emissions are allocated to each land parcel
266 in proportion to the product of the NE-EUI and the total floor area,

267 $$EC(b)_s^f = NE\_EUI_s^f \, FA(b) \qquad (1)$$

268 where the energy consumed, *EC*, in each building, *b*, is the product of the NE-EUI value, *NE_EUI*, and the floor
269 area, *FA*, for each fuel, *f*, and each building in sector, *s*. The total energy consumed, *TEC*, within the county for a
270 sector, *s*, is the sum of all the EC values across the *N* buildings in the sector,

271 $$TEC_s^f = \sum_{b=1}^{N} EC(b)_s^f \qquad (2)$$

272 To convert this to FFCO$_2$ emissions, we first calculate the fraction of the total energy consumption associated with
273 each building,

274 $$F(b)_s^f = \frac{EC(b)_s^f}{TEC_s^f} \qquad (3)$$

275 where, *F* is the fraction of *TEC* consumed in building, *b*, of sector *s*. This is then used to distribute the county total
276 FFCO$_2$ emissions as,

277 $$E(b)_s^f = E_s^f \, F(b)_s^f \qquad (4)$$

278 where *E*, is the FFCO$_2$ emissions either for the county or for building, *b*, and fuel. In allocating emissions from coal
279 consumptions, however, *NE-EUI* takes the value of "1" for all building types so that the allocated emission in a
280 building is directly proportional to the floor area.

281 **2.3.1.2 Temporal distribution**

282 The hourly time structure for buildings in the residential and commercial sectors are created via the use of eQUEST,
283 a building energy simulation tool run for each of the building classes listed in Table 2 and Table 3 and using only
284 the temporal structure of the energy consumption output (*Hirsch & Associates*, 2004). The model domain is
285 specified as the city of Los Angeles for the year 2011 with TMY weather data from the DOE (*Marion and Urban*,
286 1995). The mean building area is provided by the parcel data as described previously.
287 For the industrial buildings, a temporal profile representing the mean of industrial point source temporal surrogates
288 provided by EPA, are used (USEPA, 2015a). Figure 3 shows the hourly time profile during a one-week period in
289 April for a selected building in the residential and commercial sector, respectively.

290

291 **Figure 3. Energy consumption intensity (hourly fraction) from an eQUEST simulation on the average week in**
292 **2011 for two types of buildings: "single family detached house" and "office".**

293 **2.3.2 Industrial and commercial point sources**

294 Little space/time processing is required for industrial and commercial point source emissions since they are

295 geocoded to specific facilities/emitting stacks or similar identifiable emission points. However, visual inspection of

296 the point source locations in GIS suggested potential geocoding errors. Point source locations were reviewed by

297 searching facility names to an online address search or via the EPA's Facility Registry Service (FRS) which can link

298 the facility in question to all the reporting made to the federal government under other environmental regulations

299 (USEPA, 2013). This often returns a more accurate physical location. The geolocations considered inaccurate were

300 manually corrected. Out of the total 192 facilities with corrected locations, 13 were moved a distance of between

301 924 and 1022 km while the remaining 179 were moved 0.5 km or less. The large magnitude location changes were

302 likely transcription errors when originally recording the location coordinates.

303 A given commercial or industrial point source is typically composed of multiple emission processes or units. For

304 example, in Los Angeles County, the 2011 NEI reports a total of 3409 emission records at 842 individual facilities.

305 In some cases, the multiple emitting points at a facility are not at exactly the same geocoded point but may represent

306 different emitting points at a facility that occupies a large area of land. Most often, however, all emitting points at a

307 given facility are geocoded to the same latitude and longitude.

308 The sub-annual temporal distribution for the commercial and industrial point source emissions used temporal

309 surrogate profiles provided by the EPA, linked according to the SCC of the emission record (USEPA, 2015a).

310 **2.3.3 Electricity production**

311 As described in Section 2.2, three different data sources are used to quantify the FFCO$_2$ emissions in the Hestia-LA

312 domain: the Clean Air Markets Division (CAMD), the DOE-EIA reporting and 2011 NEI CO emissions data. In

313 2011 there were a total of 34 CAMD facilities, 228 EIA facilities and 147 NEI facilities (reported through the NEI

314 2011 point source fileset) in the Hestia-LA domain. Total electricity production emissions in the domain was 6.21

315   MtC/year exclusive of biogenic fuels and 6.68 MtC/year with biogenics included. The CAMD data is reported at

316   hourly resolution, while the DOE EIA data is reported at monthly resolution and the 2011 NEI data is reported at

317   annual resolution only. Reduction of all data to an hourly time increment was achieved by maintaining constant

318   emissions within a month or year for the DOE EIA and 2011 NEI data, respectively.

319   **2.3.4   Onroad**

320   A preliminary version of the Hestia-LA onroad emissions estimates were presented by Rao et al. (2017). The version

321   presented here uses updated data and Hestia methodologies.

322   **2.3.4.1   Temporal distribution**

323   The Hestia-LA onroad $FFCO_2$ emissions input are retrieved from the Vulcan v3.0 output spatialized to specific road

324   segments in the Hestia-LA domain and categorized by vehicle class/fuel. Hence, no further spatialization was

325   required.

326   Construction of the temporal distribution in the Hestia system relies upon the California Department of

327   Transportation (CalTrans) Performance Measurement System (PeMS) (PeMS, 2018). This dataset contains 2011

328   traffic count data collected at 5 min intervals at measuring stations along freeways and principal arterials and along

329   some minor arterials and collectors (major and minor). Aggregation of the 5-minute counts to hourly values are used

330   to construct hourly fractions for each measurement station.

331   To apply a time distribution for the $FFCO_2$ onroad emissions on each road segment, an Inverse Distance Weighting

332   (IDW) spatial interpolation method was used. A search within a neighborhood of a 10 km radius is performed from

333   the midpoint of each road segment to locate PeMS sites using a nearest neighbor searching library (Mount and Arya,

334   2010). In cases where more than one station was available, the IDW interpolation was applied; in cases where only

335   one station was available, the time structure of this station was directly assigned to the road segment in question. In

336   cases where no station was available within the 10-km neighborhood, an average temporal distribution was assigned

337   (an average of all station values in a county at that hour for that road type). This last case occurred mostly in the

338   rural portions of predominantly rural counties.

339   For local roads, PeMS data was not available in any of the counties within the Hestia-LA domain. Instead, the

340   weekday hourly time fractions were generated from Annual Average Weekday Traffic (AAWT) data supplied by

341   SCAG (*Mike Ainsworth*, 2014). The data contained five distinct time periods within a single 24 hour cycle: 6-9 am,

342   9 am-3 pm, 3-7 pm, 7-9 pm, 9 pm-6 am. Hourly time fractions for weekends were derived from the county average

343   of weekend hourly time fractions. The weekday and weekend hourly time fractions were combined to form a

344   complete week, and then replicated for all 52 weeks in the entire year. This was done because there was no

345   significant seasonality in weekday and weekend traffic across the year as observed from PeMS data.

346   **2.3.5   Nonroad**

347   The nonroad Hestia-LA $FFCO_2$ emissions are completely determined in the Vulcan system and hence, passed to the

348   Hestia-LA domain without further processing (see Gurney et al., 2018 for details). To summarize the Vulcan

349   process, California did not report FFCO$_2$ nonroad emissions to the NEI 2011 but did report nonroad CO emissions.

350   The CO emissions were converted to FFCO$_2$ using the SCC-specific ratios of CO$_2$/CO derived from all other states

351   that reported both species (a mean value). The spatial distribution of the nonroad FFCO$_2$ emissions followed two

352   approaches. Nonroad FFCO$_2$ emissions reported through the 2011 NEI point data source (5 locations, 12% of

353   nonroad FFCO$_2$ in the LA Megacity) are located in space according to the provided latitude and longitude.

354   Emissions reported through the county-scale nonroad data source utilize multiple spatial surrogates provided by the

355   EPA reflecting a series of spatial entities such as the mines, golf courses and agricultural lands. There were instances

356   in which nonroad FFCO$_2$ emissions could not be associated with a spatial entity due to missing data. These

357   emissions are spatialized by first aggregating all the offending sub-county emission elements within a county for a

358   given surrogate shape type (e.g., golf courses, mines) and then distributing these emissions evenly across the county.

359   To distribute the nonroad FFCO$_2$ emissions from the annual to hourly timescale, a series of surrogate time profiles

360   provided by the EPA are used. These temporal surrogates are comprised of three cyclic time profiles (diurnal,

361   weekly, monthly) specific to SCC that are combined to generate hourly SCC-specific time fractions for an entire

362   calendar year.

363   **2.3.6 Airport**

364   Emissions of FFCO$_2$ from airports retrieved from the Vulcan system for the Hestia-LA domain are specific to

365   geocoded airport locations. Hence, the Hestia-LA system performs the temporal distribution only. There are 374

366   commercial airports/helipads in the Hestia-LA domain totaling 0.77 MtC/year, dominated by Los Angeles County

367   (0.39 MtC/year), and LAX in particular.

368   The annual airport FFCO$_2$ emissions are distributed in time utilizing airport-specific flight volume data from four
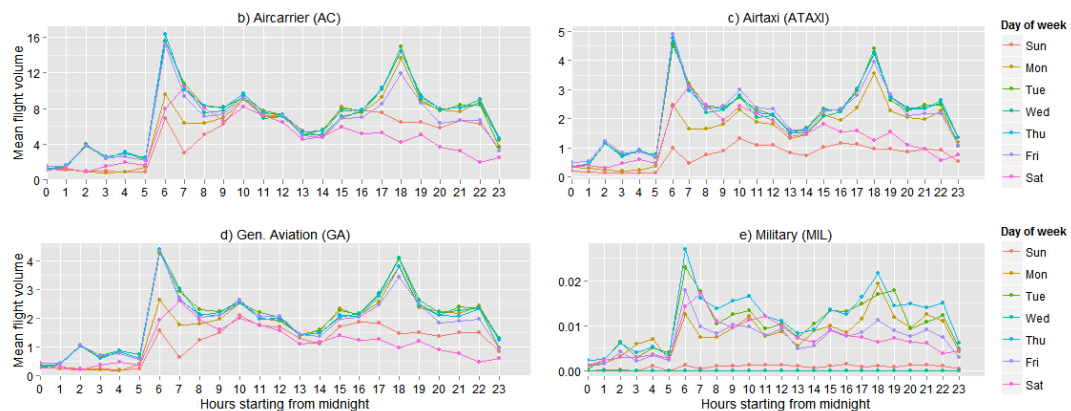
369   datasets:

370   1) The Operations Network (OPSNET) data from the Federal Aviation Administration (FAA) which reports total

371   date-specific, daily flight volume (365 values) at specific airports for specific aircraft classes (FAA, 2018a);

372   2) "AIRNAV" data which reports average daily percentage flight volume for aircraft class at US airports and

373   facilities (Airnav.com, 2018);

374   3) The Enhanced Traffic Management System Counts (ETMSC) daily flight volume data from the FAA was for two

375   airports in the Hestia-LA domain (NTD and RIV) with mostly military operations (FAA, 2018b);

376   4) The Los Angeles World Airports (LAWA) data which reports hourly flight volume for Los Angeles International

377   airport (LAX), Ontario airport (ONT), and Van Nuys airport (VNY) (LAWA, 2014).

378   For three large airports (LAX, ONT, VNY), the daily aircraft class-specific flight volume (from OPSNET) and the

379   hourly data on flight volume (from LAWA) were combined to create hourly aircraft class-specific time profiles

380   (Figure 4-6). All of the flight volume data are specific to four aircraft classes: Military (MIL), Air Carrier (AC),
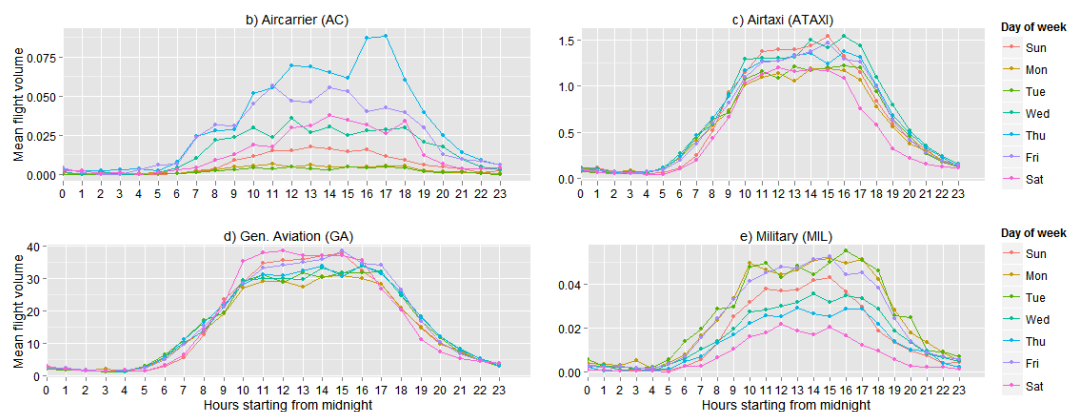
381   General Aviation (GA), and Air Taxi (AT).

382
383 **Figure 4. Average hourly flight volume at LAX for a) total, b) AC, c) AT, d) GA, and e) MIL aircraft classes**
384 **for each day of the week. The plots represent the mean diurnal cycle for all Mondays, Tuesday, Wednesdays,**
385 **and so on, given a full year of data.**

386
387 **Figure 5. Same as figure 4 but for the Ontario (ONT) airport.**

388
389 **Figure 6. Same as figure 4 but for the Van Nuys (VNY) airport.**

390 To generate hourly time profiles for all other airports in the Hestia-LA domain for which this type of detailed hourly

391 data was not available, airports first were categorized based on average daily flight volumes and average aircraft

392 class proportions from the OPSNET, AIRNAV and ETMSC data. Each airport was categorically matched to one of

393 the two non-international airports with hourly data (ONT, VNY) and the hourly time fractions adopted. LAX was

394 unique in terms of its volume and aircraft class proportions and hence was not used for any other airports. For

395 helipads and very small airports, a flat time structure was used.

396 **2.3.7 Railroad**

397 Railroad FFCO$_2$ emissions are similarly distributed in space within the Vulcan system and passed through to the

398 Hestia-LA landscape without alteration (see Gurney et al., 2018 for additional details). The Vulcan process treats

399 railroad point records somewhat differently from the railroad nonpoint records. The point source railroad emissions

400 are associated with rail yards and related geo-specific locales and are placed in space according to the provided

401 latitude and longitude. The railroad FFCO$_2$ emissions associated with the nonpoint 2011 NEI reporting contain an

402 ID variable that links to a spatial feature (rail line segment) in the EPA railroad GIS Shapefile. Nearly two-thirds of

403 the railroad emitting segments have no segment link. The sum of these "unlinked" railroad FFCO$_2$ emissions are

404 distributed to rail line within the given county according to freight statistics. The annual railroad FFCO$_2$ emissions

405 are distributed to the hourly timescale with no additional temporal structure (a "flat" time distribution).

406 **2.3.8 Commercial marine vessels**

407 The commercial marine vessel (CMV) FFCO$_2$ emissions retrieved from the Vulcan system are specific to county

408 and SCCs which are subsequently aggregated by the Hestia-LA system into emissions associated with two activity

409 categories: "port" emissions "underway". For the port CMV emissions (Figure 7), a port Shapefile from the EPA

410 was used as a reference along with a visual inspection of the coastline (USEPA, 2015a).
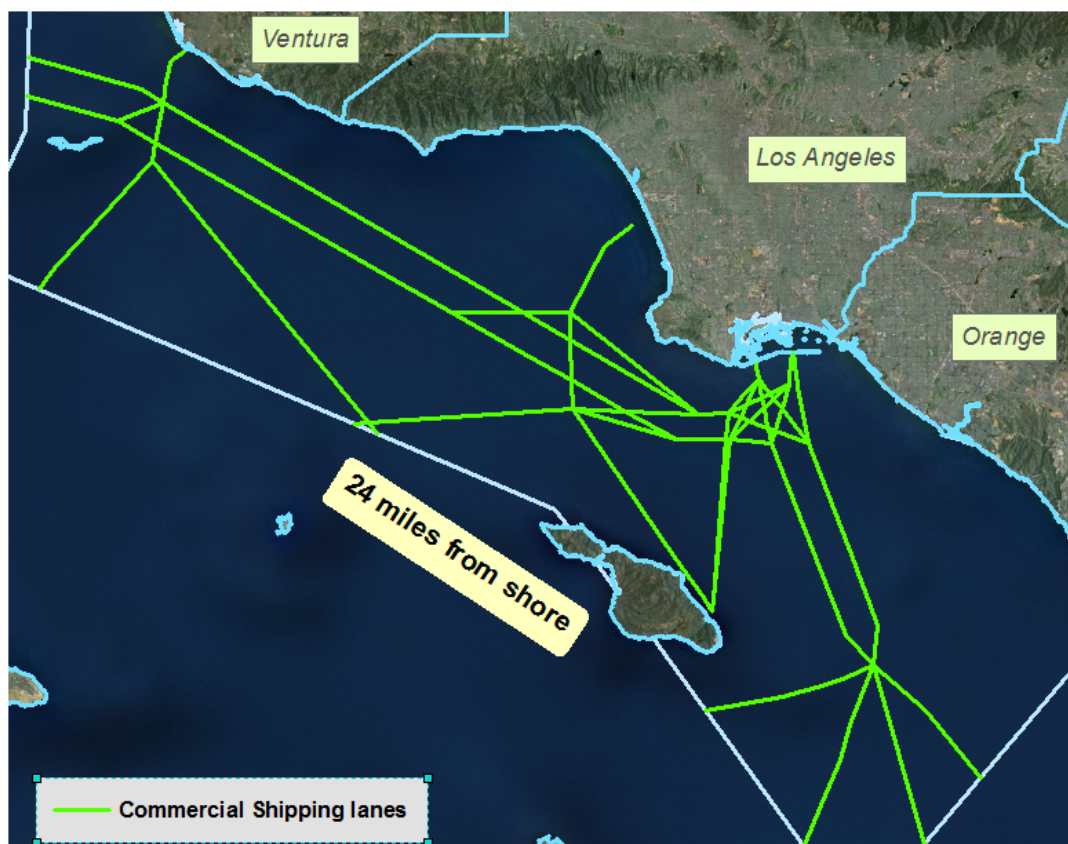

411

412 **Figure 7. The 6 ports in the Hestia-LA domain to which Vulcan FFCO$_2$ port emissions are allocated.**

413   Allocation of the FFCO$_2$ emissions designated as "underway" used a polyline Shapefile (Figure 8) of commercial
414   shipping lanes in California provided by CARB (Alexis, 2011). The shipping lanes for each county were bounded so
415   that only lanes between the exterior of ports and a distance of 24 miles from the port exterior, were included. County
416   total FFCO$_2$ emissions were then distributed evenly to these shipping lanes on a per unit length basis individually for
417   each of the three counties. Each shipping lane segment receives its length fraction of the annual total of underway
418   emissions.

419
420   **Figure 8. Commercial Marine Vessel (CMV) shipping lanes in the Hestia-LA to which Vulcan FFCO$_2$**
421   **underway emissions are allocated.**

422   The time profile was based on the Marine Emissions Model (MEM) developed by CARB. MEM had marine vessel
423   activity data which includes the arrival time of ocean-going vessels for all ports in California spanning the 2004 to
424   2006 time period (Alexis, 2011). This hourly dataset was analyzed using a Fourier time series which allowed for an
425   isolation of the dominant cycles of ship traffic in the data. Results from the Fourier fit were then used to fill in the
426   missing hours. Weekday hours were examined separately from weekend hours to isolate potential differences in
427   traffic volume. Three cycles resulted: a 24-hour diurnal cycle, a weekly cycle and a monthly cycle. These were
428   applied to all years of the annual FFCO$_2$ emissions to create an hourly distribution at each of the CMV ports within
429   the domain.

2.3.9 Cement

Emissions of $FFCO_2$ from cement production facilities retrieved from the Vulcan system for the Hestia-LA domain are specific to geocoded facility locations. CO_2 is emitted from cement manufacturing as a result of fuel combustion and as process-derived emissions [van Oss, 2005]. The emissions from fuel combustion are captured in the industrial sector. The process-derived CO_2 emissions result from the chemical process that converts limestone to calcium oxide and CO_2 during "clinker" production (clinker is the raw material for cement which is producing by grinding the clinker material). These emissions are reported as cement sector emissions

These emissions are fully calculated, spatialized and temporalized in the Vulcan v3.0 system and passed directly to the Hestia-LA landscape. The cement facilities are geocoded with some corrections to provide more accurate placement of the emission stacks.

2.4 Gridding

The county-level $FFCO_2$ emissions inventory, which has been distributed into the point, line and polygon features by sector, are rasterized into a sector-specific and time-resolved gridded form under a common grid reference. This grid reference divides the entire Hestia-LA domain into 509-by-342 1 km x 1 km grid cells on the California State Plane Coordinate System. The grid reference is made into "fishnet" in the Shapefile format with 509-by-342 square geometries.

The first step of the gridding procedure is to perform a spatial intersection operation between the fishnet and each of the sectoral emissions layers in ArcGIS. The output of an intersection operation is a new set of features common to both input layers. The emissions value of each feature in the intersection output was scaled by the ratio of the spatial footprint of the feature to that of the original feature in the sectoral emissions layer. For line-source and polygon-source emissions layers, the spatial footprint represents the line length and polygon area respectively. For point-source layers, the footprint is equal to 1.

2.5 Uncertainty

Uncertainty estimation for Hestia results are challenging owing to the fact that many of the datasets used to construct the flux results are not accompanied by uncertainty or traceable to transparent sources or methods. The approach taken for the Hestia-LA v2.5 results was to conservatively estimate the uncertainty based on available comparisons to Hestia results and exploration of the dominant components of the Hestia output. The first of these is a comparison of the Hestia-Indianapolis (Hestia-Indy) results to an inverse-estimation of fluxes in the INFLUX project (Gurney et al., 2017). In that study, it was shown that the Hestia-Indy whole-city $FFCO_2$ emissions result agreed with an inverse estimate (Lauvaux et al., 2016) within 3.3% (CI: -4.6% to +10.7%). This suggests both potential bias (3.3%) and an estimation uncertainty (~7.5%). This comparison was accomplished by estimating portions of the carbon budget, included in the inverse estimate, but not explicitly included in the Hestia-Indy result. Most importantly, biosphere respiration estimated from chamber studies at commensurate urban latitudes combined with a remote-sensing based approach to quantifying the available vegetated landscape. This comparison, it should be noted, is for a single city (Indianapolis) for a single time period. We directly sum the random and systematic error and use this in the current study to represent the Hestia-LA whole-city uncertainty (a 95% CI), rounded up to 11%.

466   The next element for consideration with a conservative uncertainty estimate is the work done to compare two
467   different electricity production $FFCO_2$ estimates in the US. This work (Gurney et al., 2016) found that one-fifth of
468   the facilities had monthly $FFCO_2$ emission differences exceeding -6.4%/+6.8% for the year 2009 (the closest
469   analyzed year to the 2011 analysis examined here). The distributions of emissions of the two datasets were not
470   normally distributed nor were the differences. Hence, a typical gaussian uncertainty estimate cannot be made –
471   rather, the difference distribution was represented by quintiles of percentage difference. Hence, these values cannot
472   be cast within the context of other normally-distributed errors. However, we conservatively consider the quintile
473   value (the positive and negative tails) as a one-sigma value and 13% as a two-sigma value. The contribution of
474   electricity production is important to urban $FFCO_2$ emissions uncertainty given how large power production can be
475   within the total urban $FFCO_2$ context. For example, in the Los Angeles Megacity electricity production accounts for
476   19% of the total $FFCO_2$ emissions. The percentage differences can act as a form of uncertainty at the pointwise or
477   (conservatively) the gridcell scale, though only representative of the type of uncertainties represented by electricity
478   production point sources.
479   Finally, an initial assessment of the range of two critical parameters in the Vulcan/Hestia estimation is included as
480   part of the conservative uncertainty estimation. The two critical parameters are the CO emissions factor and the CO_2
481   emissions factor. Primarily for the CO EF, there is a range of potential values for each application (combination of
482   fuel category and combustion technology) though that range is not represented by a well-populated distribution of
483   values, but rather a discrete set of values within the data sources described in Gurney et al. (2009). Furthermore, the
484   expectation is that the CO EFs would not be normally distributed even were there to be a well-populated distribution
485   of values (i.e. many literature estimates of the same fuel/combustion technology) owing to the nature of CO
486   emissions from fuel combustion. This is driven by both the variation in combustion conditions for a given
487   fuel/technology combination and the variation is CO EF values across combustion technology. The distribution
488   would likely be a positively skewed "heavy" or "long" tailed distribution. For the current study, a range of the CO
489   and CO_2 EF values culled from the literature are conservatively assigned a one-sigma uncertainty of 10% or a two-
490   sigma value of 20%. Like the electricity production analysis in the previous paragraph, the uncertainty associated
491   with the CO and CO_2 emission factors is a gridcell-scale uncertainty (as opposed to whole city where error
492   cancelation occurs) and is independent of the electricity production uncertainty estimate (the CO and CO_2 EF values
493   are not used in the electriity production sector but in the other point sources and nonpoint sources).
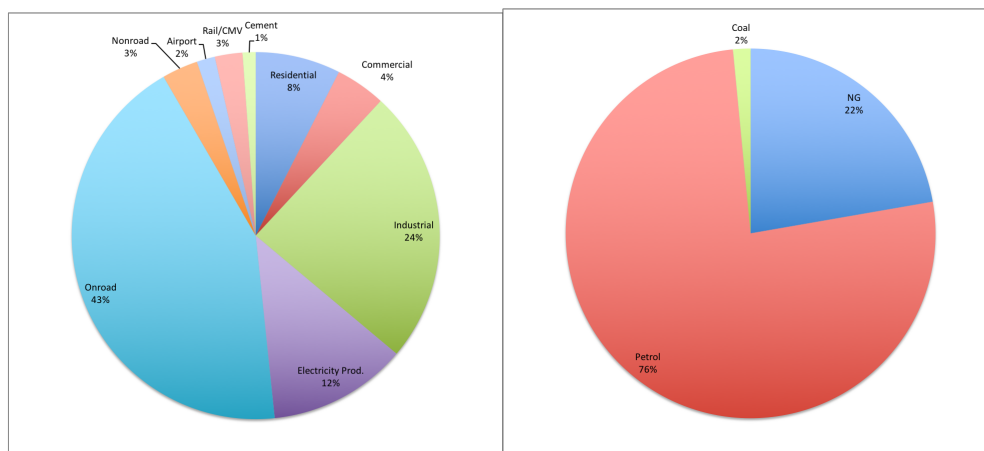494   These latter two uncertainty are more representative of gridcell-scale uncertainties and sum them in quadrature to
495   arrive at a gridcell-scale uncertainty (95% CI) of 23.4% or conservatively rounded to 25%. Work is underway that
496   includes a complete input parameter range for the Hestia emissions data results to more formally assign uncertainty
497   at multiple scales.

498   **3 Results**

499   The total 2011 emissions for the Hestia-LA domain are 48.06 ± 5.3 MtC/yr (Figure 9, Table 5). Transportation
500   accounts for the largest share (24.27 ± 2.7 MtC/yr) of the total and within the transportation sector, onroad emissions
501   account for the largest portion (20.81 ± 2.3 MtC/yr). The next largest sectors are the industrial (11.65 MtC/yr ± 1.3)
502   and electricity production (5.88 ± 0.76 MtC/yr) sectors, respectively. Onroad, electricity production, residential and

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503 industrial FFCO$_2$ emissions make up 86% of the total. Petroleum accounts for almost 75% of the total LA Megacity

504 fuel consumption for direct FFCO$_2$ emissions consistent with the dominance of the transportation and industrial

505 sectors which are mostly reliant on petroleum fuels. Los Angeles County dominates emissions in the five counties of

506 the Hestia-LA domain accounting for 55% of the total FFCO$_2$ emissions. This is followed by San Bernardino,

507 Orange, Riverside, and Ventura counties, respectively. Los Angeles and San Bernardino counties are dominated by

508 onroad and industrial FFCO$_2$ emissions, while onroad emissions account for the largest share, by far, in the

509 remaining three counties. Not surprisingly, Los Angeles county has the largest CMV FFCO$_2$ emissions among the

510 five counties owing to the port of Los Angeles which hosts a large amount of international commercial shipping. At

511 0.61 ± 0.067 MtC/yr, it rivals in emission magnitude the combination of residential and commercial building

512 emissions in each of the other four counties.

Figure 9. Total FFCO$_2$ emissions proportions for the Hestia-LA domain. a) FFCO$_2$ emission proportions by sector; b) FFCO$_2$ emission proportions by fuel category.
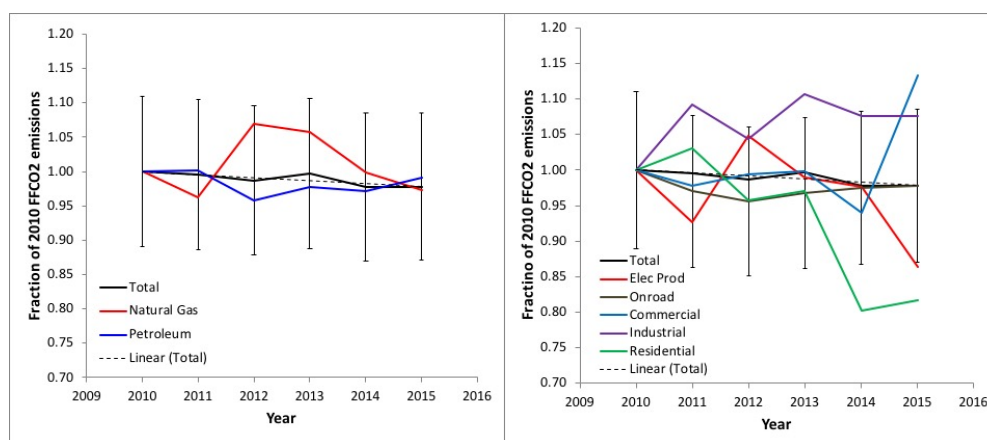
Table 5. Sectoral FFCO$_2$ emissions in the five Hestia-LA domain counties for the year 2011. Units: MtC/yr.

Sector	Los Angeles (MtC/yr)	Orange (MtC/yr)	San Bernardino (MtC/yr)	Riverside (MtC/yr)	Ventura (MtC/yr)	Total (MtC/yr)
Residential	2.00	0.64	0.40	0.36	0.20	3.59
Commercial	1.47	0.12	0.21	0.24	0.071	2.12
Industrial	7.27	0.94	2.99	0.25	0.20	11.65
Electricity production	2.73	0.69	1.54	0.71	0.21	5.88
Transportation	12.95	3.83	3.58	2.88	1.02	24.27
Onroad	11.03	3.46	2.98	2.51	0.82	20.81
Nonroad	0.79	0.27	0.19	0.19	0.087	1.52
Airport	0.39	0.06	0.14	0.11	0.070	0.77
Railroad	0.13	0.028	0.27	0.072	0.010	0.51
CMV	0.61	0.012	0	0	0.037	0.66
Cement	0	0	0.55	0.0077	0	0.55
Total	**26.42**	**6.22**	**9.28**	**4.45**	**1.70**	**48.06**

517 Total emissions in the LA Megacity show a small downward trend over the 2010-2015 time period of 0.44%/year

518 which is a statistically significant trend (slope: -0.21 MtC/yr; CI: -0.397, -0.023). Individual sectors show greater

519 variation there are compensating temporal changes among the individual sectors (Figure 10). The residential sector

520 showed a relatively large decline in 2014, though due to its relatively small portion of total emissions, has limited
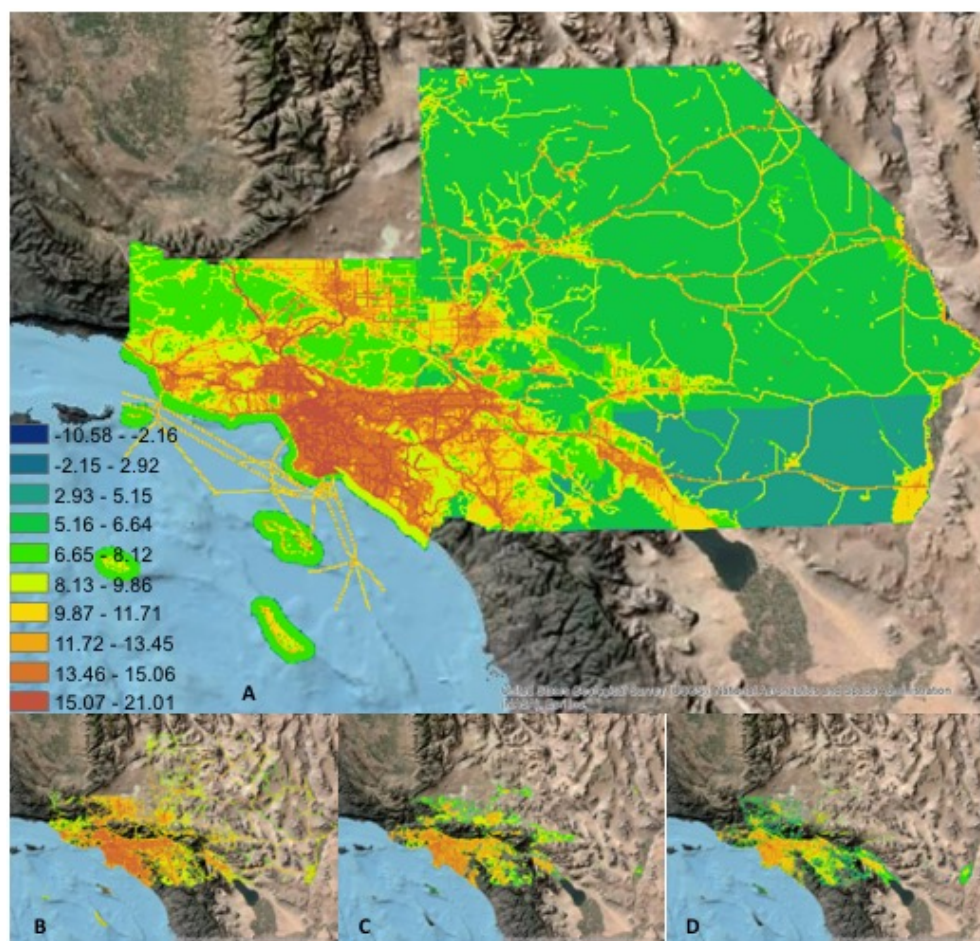
521   impact on the total temporal variation from 2010-2015. Similarly, 2015 showed a large increase in commercial

522   sector emissions which also do not translate to large changes in the total FFCO$_2$ emissions time series. The relative

523   temporal stability of the industrial and onroad FFCO$_2$ emissions sectors combined with their large share of the total

524   FFCO$_2$ emissions are reflected in the total emissions trend. When categorized by fuel type, natural gas FFCO$_2$

525   emissions exhibited the greatest variation with a maxima in 2012 and to a lesser extent 2013, driven primarily by

526   consumption in the electricity production sector.

527

Figure 10. Fractional changes over the 2010 to 2015 timeframe in LA Basin FFCO$_2$ emissions. a) by fuel category; b) by sector. Whole-city error provided for the total FFCO$_2$ emissions only.

530   Spatial distribution of the Hestia-LA FFCO$_2$ emissions demonstrate the importance of the populated areas and road-

531   intensive portions of the domain in the overall emissions (Figure 11). The constant emissions that appear over large

532   areas, particularly in San Bernardino and Riverside counties, are due to the nonroad FFCO$_2$ emissions which have

533   relatively simple spatial distribution proxies with considerable areal extent.
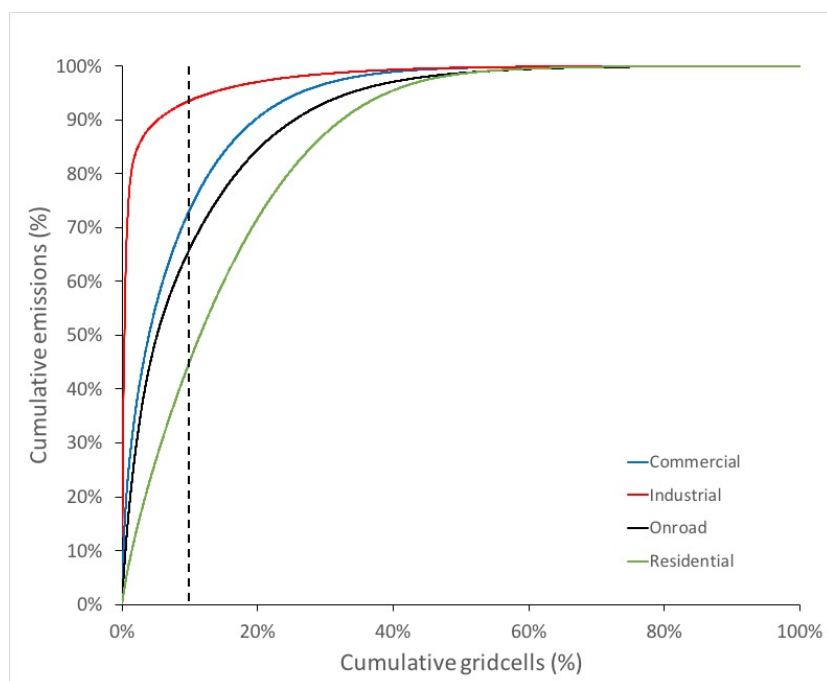
534

535

Figure 11. Hestia-LA v2.5 FFCO$_2$ emissions for the year 2011 represented on a 1 km x 1 km grid. a) total FFCO$_2$ emissions; b) onroad FFCO$_2$ emissions; c) residential FFCO$_2$ emissions; d) commercial FFCO$_2$ emissions. Units: natural logarithm KgC/gridcell/yr.

539 Figure 12 shows the cumulative FFCO$_2$ emissions across four of the sectors for which the 1 km^2 gridcell

540 accumulation is most appropriate: the commercial, industrial, onroad, and residential sectors. The other FFCO$_2$

541 emission sectors (airport, electricity production, cement) are not included in Figure 12 because they are dominated

542 by a few points, have limited spatial distribution (railroad) or no spatial variance (nonroad). The accumulation of

543 FFCO$_2$ emissions at the threshold by which 10% of the gridcells are accumulated is noted on the figure. For the

544 industrial sector, 10% of the largest emitting gridcells account for 93.6% of the total industrial sector emissions. For

545 the commercial sector this occurs at 73.4% of the accumulated gridcells. For the onroad and residential sectors this

546 occurs at 66.2% and 45.3%, respectively. This demonstrates two important points about the FFCO$_2$ emissions in the

547 Los Angeles Megacity (and most cities). First, the emissions have very high spatial variance with few gridcells

548 accounting for a large portion of the total FFCO$_2$ emissions. Second, this is particularly true for the industrial sector,

549 driven by the fact that it is comprised of a large proportion of point emitters. This is somewhat true of the

550   commercial sector which does have some pointwise data within the original NEI reporting. Of the remaining two

551   sectors, which contain no pointwise spatial emitters, the majority (66.2%) of the onroad emissions are captured in

552   the largest 10% while the residential sector, being less concentrated, shows an accumulation just short of the 50%

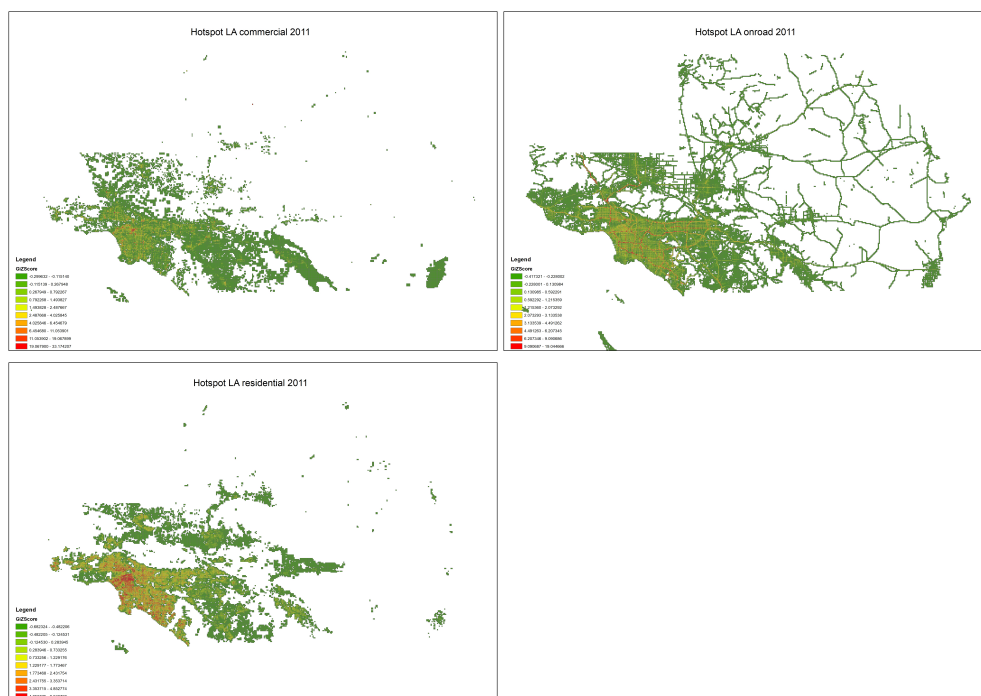553   threshold at a 10% gridcell accumulation threshold.

554

Figure 12. Cumulative FFCO$_2$ emissions according to key sectors in the Hestia-LA FFCO$_2$ emissions data product. The dashed line at 10% cumulative grid cells is given for reference. See text for details.

557   An important attribute of estimating urban emissions at fine space and time scales is the resulting clustering in space

558   (and time) of the emissions and the varying patterns of the clustering across the emitting sectors. Figure 13 provides

559   an analysis of spatial clustering using the *Getis-Ord-Gi* statistic which provides a score that measures statistically

560   significant departures from random local clustering (*Getis and Ord*, 1992). The three sectors included in this

561   analysis are the residential, commercial and onroad sectors. The onroad sector shows a more widely dispersed

562   clustering pattern with local "hotspots" generated by high traffic flow points and traffic congestion, primarily on the

563   interstate network coincident with a greater density of commercial and residential activity. The residential sector

564   exhibits less extensivity compared to the onroad FFCO$_2$ emissions clustering but with larger individual hotspot

565   areas. Particularly large clustering occurs from the coast centered on Santa Monica and Marina del Rey and

566   extending East and North through West Hollywood on to Pasadena and Alhambra. Other hotspots occur in the

567   Manhattan Beach to Redondo Beach corridor, the Burbank and Glendale area and the coastal portion of Orange

568   county (e.g. Huntington Beach, Newport Beach). The commercial sector shows the a similar overall extensivity to

569   the residential sector but with less extensive individual hotspots associated with commercial building clusters.

23

570

571
572 **Figure 13. The *Getis-Gi* z-score for Hestia-LA FFCO$_2$ emissions across three sectors; a) commercial; b)**
573 **onroad; c) residential.**

574   There are very few potential sources for comparison to the Hestia FFCO$_2$ emissions as few inventory efforts have

575   been accomplished at the sub-state spatial scale in the United States. However, the Southern California Association

576   of Governments (SCAG) have completed a regional greenhouse gas emissions inventory for a base year period of

577   1990-2009 with projections out to the year 2035 (SCAG, 2012). The SCAG inventory reflects two components that

578   make comparison to the Hestia-LA FFCO$_2$ emissions data product imperfect. First, the domain considered in the

579   SCAG inventory includes Imperial county, a county not included in the Hestia-LA domain. However, Imperial

580   county is estimated to be less than a few percent of the SCAG domain total. For example, Imperial county onroad

581   VMT is 1.9% of the SCAG domain total. The Imperial county retail sales of electricity is 1.1% of the SCAG domain

582   total. The other distinction is that the SCAG inventory reports total GHGs, inclusive of both methane (CH$_4$) and

583   nitrous oxide (N$_2$O). However, in the sectors and activities used in comparing the SCAG inventory to the Hestia-LA

584   FFCO$_2$ emissions data product, both CH$_4$ and N$_2$O are negligibly small. Hence, small differences (<5%) could be

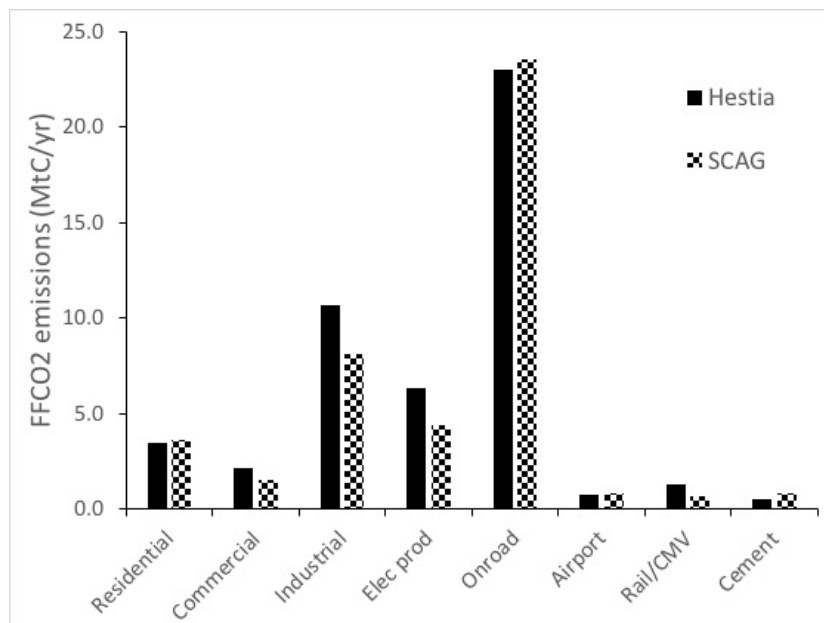585   due to these categorical discrepancies.

586   Figure 14 shows a 2010 comparison between the two estimates using the comparable sector divisions. The Hestia-

587   LA FFCO$_2$ emissions estimate is 10.7% larger than the SCAG estimate, 95% of the difference (4.46 MtC/yr) owing

588   to the larger industrial and electricity production FFCO$_2$ emissions in the Hestia estimate. We have included the

589   nonroad sector in the onroad category as the SCAG inventory did not explicitly include a nonroad sector. SCAG

590   documentation suggests that the nonroad sector is included in the forecasts for the residential, commercial and

591   industrial sectors (SCAG, 2012, page C-10) but further details on the base year estimates could not be found and no

592   mention is made in the report where these sectors are described. If the Hestia nonroad estimate (1.56 MtC/yr) were

593   not allocated to onroad but distributed to the residential, commercial and industrial sectors it would exacerbate the

594   difference in the onroad, commercial and industrial sectors.

595

596   **Figure 14. Comparison of sector-specific FFCO$_2$ emissions for the year 2010 between the Hestia-LA and**
597   **SCAG estimates. Units: MtC/yr.**

598   The California Energy Commission archives energy consumption data for both natural gas and electricity

599   (http://ecdms.energy.ca.gov/). The data is archived as specific to the residential sector and the non-residential sector.

600   Because of ambiguities regarding the non-residential sector definition, we compare the reported values by county for

601   the residential only (Table 6). Good agreement for natural gas FFCO$_2$ emissions is achieved for the Los Angeles

602   Megacity as a whole (<1%) with some variation at the scale of the individual counties. Agreement with the CEC

603   estimate is better than that found for the comparison with the SCAG inventory (Hestia being 3.1% lower than the

604   SCAG residential NG FFCO$_2$ estimate).

605   **Table 6. Residential natural gas FFCO$_2$ emissions in the five Hestia-LA domain counties for the year 2011**
606   **compared to estimates from the California Energy Commission (CEC). Units: MtC/yr.**

County	Hestia	CEC	diff (%)
Los Angeles	1.94	1.98	-2.0%
Orange	0.63	0.59	5.7%
San Bernardino	0.40	0.39	0.8%
Riverside	0.35	0.39	-11.1%
Ventura	0.19	0.18	6.5%
LA Megacity	**3.51**	**3.54**	**-0.9%**

607   Average hourly variations in FFCO$_2$ emissions are sensitive to both the sector and spatial location. Figure 15

608   presents annual mean diurnal patterns specified by county and sector (the railroad or cement sectors were

609   constructed with no diurnal cycle and hence is not shown). As noted previously, Los Angeles county shows the

610   greatest emissions overall, particularly for the commercial marine vessel sector where the port of Los Angeles

611   dominates. The commercial, residential, onroad and CMV sectors exhibit two maxima, one in the morning (~5-10

612   am, local time) and another in the afternoon/evening. In the commercial sector, this afternoon/evening maximum

613   occurs later in this time period centered on 9 pm local time, coinciding with retail closing schedules. The maximum

614   CMV emissions are shifted by roughly two hours earlier in the day for both the morning and afternoon/evening

615   peaks. The afternoon/evening maximum for the onroad sector shows an afternoon/evening maximum that is of

616   longer duration than that in the morning with emissions gradually rising after the midpoint of the day, local time. In

617   addition to large daily variations, the onroad sector contains a significant weekly temporal pattern with emissions

618   largest on Monday and smallest on Saturday (Figure 16).

619   Diurnal patterns in onroad and airport $FFCO_2$ emissions have a single maximum at the middle of the day but broadly

620   extending across all daylit hours. In the case of the nonroad emissions, this is simply a reflection of the EPA

621   temporal surrogate applied. In the case of the airport $FFCO_2$ emissions, the time structure reflects the reported air

622   traffic volume at the major airports in the LA Megacity. Finally, the industrial and electricity production sectors

623   maintain relatively constant emissions across all 24 hours. In the case of the industrial sector, this reflects the

624   integration of industry-specific EPA temporal surrogates within a given county. For the electricity production sector,

625   the time structure is primarily driven by the stack-monitored emissions and shows a slightly greater emission in the

626   evening hours compared to all other hours.

627   The diurnal patterns are consistent across all five counties with the exception of the commercial sector where there

628   are small differences in the maximum point of the morning emissions in San Bernardino and Ventura counties

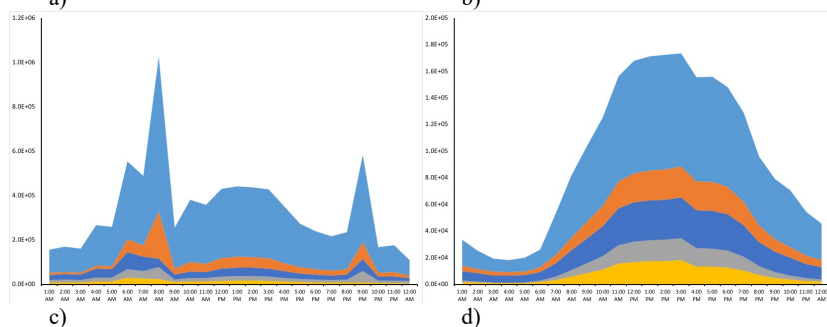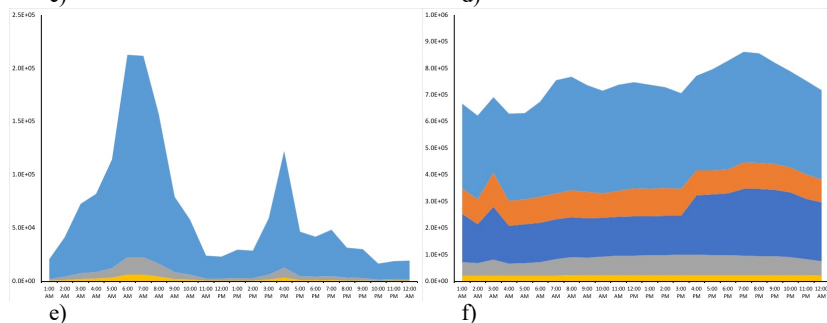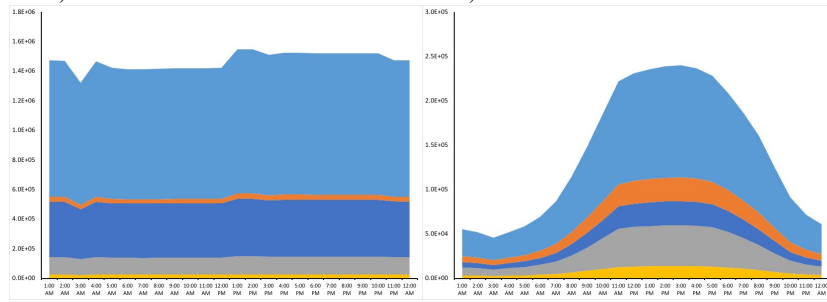629   compared to the other LA Megacity counties.

630

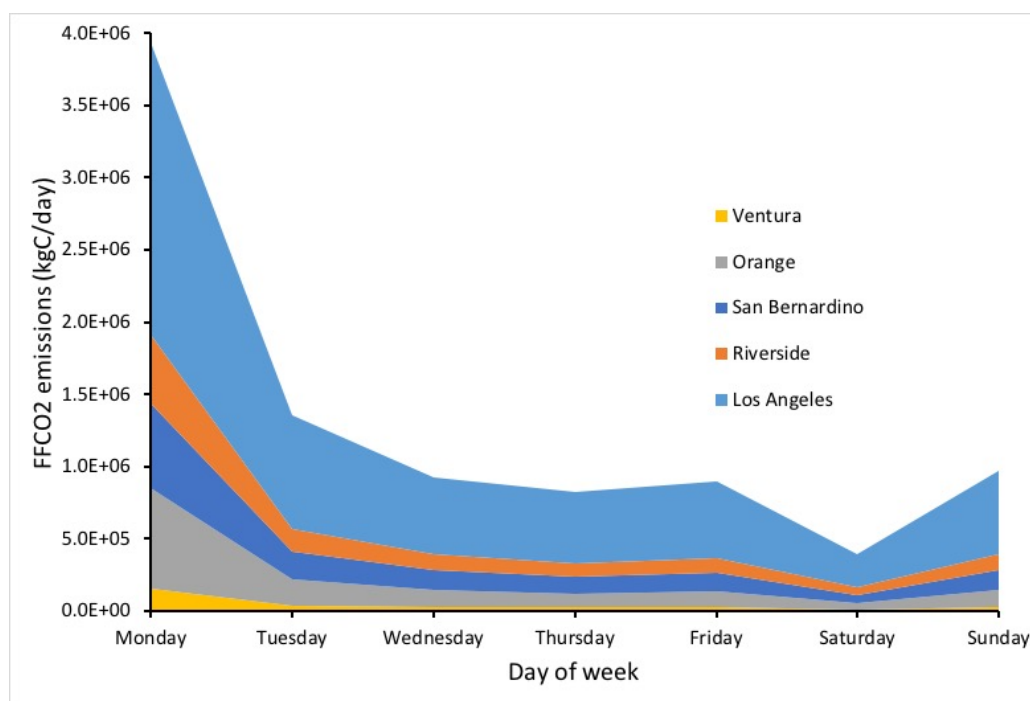**Figure 15. Average daily FFCO₂ emissions in the Hestia-LA v2.5 data product for five counties across eight sectors. A) residential; b) onroad; c) commercial; d) airport; e) commercial marine vessel; f) electricity production; g) industrial; h) nonroad. Note: different scale range on each plot. Units: kgC/hour.**

643

Figure 16. Average weekly onroad FFCO$_2$ emissions from the Hestia-LA v2.5 data product for five counties.
644
Units: kgC/day
645

646 **4 Discussion**

647 The first Hestia urban FFCO$_2$ emissions data product was produced for the Indianapolis domain (Gurney et al.,

648 2012). As an outcome of the Hestia effort, a large multifaceted effort, the Indianapolis Flux Experiment (INFLUX),

649 emerged (Whetstone et al., 2017; Davis et al., 2017). INFLUX aims to advance quantification and associated

650 uncertainties of urban CO$_2$ and CH$_4$ emissions by integrating a high-resolution bottom-up emission data product,

651 such as Hestia, with atmospheric concentration measurements (Turnbull et al., 2015; Miles et al., 2017; Richardson

652 et al., 2017), flux measurements (Cambaliza et al., 2014; 2015; Heimberger et al., 2017), and atmospheric inverse

653 modeling. In addition to its use as a key constraint in the INFLUX atmospheric inverse estimation (Lauvaux et al.,

654 2016), Hestia has been informed by atmospheric observations making it useable as a standalone high-resolution flux

655 estimate offering a detailed space-time understanding of urban emissions. Begun in the late 2000s, INFLUX has

656 explored many aspects of the individual elements of a scientifically-driven urban flux assessment (e.g. Wu et al.,

657 2018) in addition to demonstrating potential reconciliation between Hestia and the atmospheric measurements

658 (Gurney et al., 2017; Turnbull et al., 2018). Similar efforts are ongoing in the Salt Lake City (Mitchell et al., 2016;

659 Lin et al., 2018) and Baltimore (Martin et al., 2018) domains with a different arrangement of atmospheric

660 monitoring and modeling. As with INFLUX, a Hestia FFCO$_2$ emissions data product was produced in each domain

661 (Patarasuk et al., 2016; Gurney et al., 2018).

The Hestia Los Angeles Megacity effort was developed under the Megacities Carbon Project framework (https://megacities.jpl.nasa.gov/portal/). It was designed to serve the Megacities Carbon Project in a similar capacity to its role in INFLUX. The Hestia-LA results are unique in that it is the first high-resolution spatiotemporally-explicit inventory of $FFCO_2$ emissions centered over a megacity. Presented here at the 1 km^2 spatial and hourly temporal resolution, the emissions can be represented at finer spatial scales down to the individual building, though with higher uncertainty. While policy emphasis in California thus far has been focused on CH_4 emissions (Carranza et al., 2017; Wong et al., 2016; Verhulst et al., 2017; Hopkins et al., 2016), work is ongoing to use the extensive atmospheric CO_2 observing capacity in the Los Angeles domain (e.g. Newman et al., 2016; Wong et al., 2015; Wunch et al., 2009) within an atmospheric CO_2 inversion. This will offer an important evaluation of the Hestia-LA emissions for which limited independent evaluation is currently available.

The potential of the Hestia-LA $FFCO_2$ emissions to enable or assist with policymaking in the cities, counties or metropolitan planning domain of the overall Southern California area is considerable. The traditional urban inventory approach, such as accomplished by many cities as part of their climate action plans, are whole-city accounts, often specific to sector, that follow one of a few inventory protocols. Given the challenges of data acquisition and the idiosyncrasies of protocol choice and needs, the traditional urban inventories are difficult to compare across cities and hence, aggregate reliably in a metropolitan domain such as the LA Megacity. Importantly, without space and time explicit emissions information, they are difficult to calibrate with atmospheric measurements and hence, evaluate against this important scientific constraint. The Hestia-LA $FFCO_2$ emissions approach attempts to overcome these limitations to traditional inventory work. By quantifying emissions at the scale of individual buildings and road segments, with process detail such as the sector, fuel, and combustion technology, Hestia results can be organized according to most of the protocols in use by cities. This explicit space and time detail also allow for calibration to atmospheric measurements, for which emission location and time structure is essential.

The state of California continues to lead the nation in climate policy with numerous legislative and executive orders outlining both general reduction goals and specific policy instruments. The California Global Warming Solutions Act (Assembly Bill 32) passed in 2006, specifies a statewide reduction in greenhouse gas emissions to 1990 levels by the year 2020 (https://www.arb.ca.gov/cc/ab32/ab32.htm). Furthermore, the bill requires reporting and verification of reductions in order to demonstrate compliance. Executive order B-30-15 and Senate Bill, SB 32 have built on this with an aim to reduce emissions 40% below 1990 levels by 2030 and 80% below 1990 levels by 2050, respectively (https://www.gov.ca.gov/2015/04/29/news18938/; https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB32). Ultimately, much of the specific action needed to meet these goals will rest upon local governments and authorities. Given that 87% of the state population resides in urban areas and nearly half of state population resides in the Los Angeles Megacity, the cities and counties that comprise the Los Angeles metropolitan area have a central role to play in achieving the statewide climate change policy goals. The city of Los Angeles, the largest individual city in the metro region, has specified goals consistent with the state commitments, expecting to reduce greenhouse gas emissions 35% below 1990 levels by the year 2030 (http://environmentla.org/pdf/GreenLA_CAP_2007.pdf). To meet these reduction goals, policy actions will become increasingly difficult to achieve at no- or low-cost and economic efficiency will become central to making policy choices.

700   The most important attribute of the Hestia-LA approach, therefore, is the potential it offers for targeting urban CO_2

701   reduction policy more efficiently. As shown in Figures 12 and 13, $FFCO_2$ emissions are highly variable in space and

702   typically cluster in concentrated areas. In choosing specific policy approaches and instruments, this offers Los

703   Angeles policymakers the ability to target specific neighborhoods, road segments, or commercial hubs, where

704   policies will achieve the greatest reduction for resources expended. This rests on the argument that specificity leads

705   to efficiency. As all cities, including those in the Los Angeles Megacity, move towards those aspects of carbon

706   emission reductions that are not part of the "low hanging fruit" policy instruments, competition for limited resources

707   and policy justification will increase. Having information that targets the most efficient and effective emission

708   reduction investments, established by independent rigorous scientific information, will be at a premium. For

709   example, if a small proportion of the commercial sector buildings in the LA Megacity account for a large proportion

710   of the $FFCO_2$ emissions, knowing the location of these buildings and targeting energy efficiency programs to those

711   buildings, may offer the most economically efficient route to emissions reductions in the commercial sector. A

712   similar argument can be made in the onroad sector due to the clustering of large onroad emitting gridcells and

713   specific road-class attributes (see Rao et al., 2017).

714   A number of caveats are worth mentioning in association with the Hestia-LA v2.5 $FFCO_2$ emissions results. With

715   Vulcan v3.0 as the starting point for the quantification in Hestia, errors in Vulcan will be passed to Hestia, with a

716   few exceptions. Of particular note are the industrial sector and more specifically, refining operations which have

717   limited emissions reporting. These remain difficult to quantify due to the range of CO emission factors representing

718   many of the combustion processes undertaken at these large and complex facilities. The uncertainty estimation

719   described remains limited and there are additional sources of uncertainty that must be quantified such as categorical

720   errors (e.g. mis-specification of fuel category or road class), errors in spatial accuracy and spatial error correlation.

721   Quantifying these contributions to the overall uncertainty presented here remain a task for future work.

722   **5 Data availability, policy and future updates**

723   The Hestia-LA v2.5 emissions data product can be downloaded from the data repository at the National Institute

724   of Standards and Technology (https://doi.org/10.18434/T4/1502503) and is distributed under Creative Commons

725   Attribution 4.0 International (CC-BY 4.0, https://creativecommons.org/licenses/by/ 4.0/deed.en). The Hestia-LA

726   v2.5 $FFCO_2$ emissions data product is provided as annual and hourly (local and UTC versions) 1 km x 1 km

727   NetCDF file formats, one file for each of the 6 years (2010-2015). The hourly files are approximately 2.9 GB each.

728   The annual files are 0.34 GB each.

729   Attempts will be made to update the Hestia-LA $FFCO_2$ emissions on a roughly bi-annual basis, depending upon

730   support, the availability of updates to the Vulcan $FFCO_2$ emissions data product, and updates to the additional data

731   sources described in this study.

732   **6 Conclusion**

733   The Hestia Project quantifies urban fossil fuel CO_2 emissions at high space- and time-resolution with application to

734   both scientific and policy arenas. We present here the Hestia-LA version 2.5 $FFCO_2$ emissions data product which

735   represents hourly, 1 km^2, sector-specific emissions for the five counties of the Los Angeles metropolitan area for the

736   2010 to 2015 time period. The methodology relies on the results of the Vulcan Project (version 3.0) further

737   enhancing and distributing emissions to the scale of individual buildings and road segments with local data sources

738   acquired from local government agencies. Each sector is quantified using data sources and spatial/temporal

739   distribution approaches distinct to the sector characteristics. The results offer a detailed view of FFCO$_2$ emissions

740   across the LA Megacity and point to the extreme spatial variance of emissions. For example, 10% of the 1 km^2

741   emitting gridcells account for 93.6%, 73.4%, 66.2%, and 45.3% of the emissions in the industrial, onroad,

742   commercial, and residential sectors, respectively. We find that the LA Megacity emitted 48.06 ± 5.3 MtC/yr in the

743   year 2011, dominated by Los Angeles county (26.42 ± 2.9 MtC/yr) and from a sector-specific viewpoint, dominated

744   by the onroad sector (20.81 ± 2.3 MtC/yr). Hestia FFCO$_2$ emissions are 10.7% larger than the inventory estimate

745   generated by the local metropolitan planning agency, a difference that is driven by the industrial and electricity

746   production sectors. Good agreement is found (<1%) when comparing residential natural gas FFCO$_2$ emissions to

747   utility-based reporting at the county spatial scale. The largest temporal variations are found in the diurnal cycle with

748   the residential, commercial, onroad, and commercial marine vessel emissions showing to maxima, one in the

749   morning and a second in the afternoon/evening. Airport and nonroad emissions, by contrast show broad maxima

750   across the daylit hours. Finally, the industrial and electricity production sectors show little diurnal variation across

751   24 hours. The onroad sector also exhibits variation in the weekly distribution of emissions with maximum FFCO$_2$

752   emissions on Monday and minimum emissions on Saturday.

753   The Hestia-LA v2.5 FFCO$_2$ emissions data product offers the scientific and policymaking communities

754   unprecedented spatially and temporally-resolved information on FFCO$_2$ emission sources in the Los Angeles

755   Megacity. As part of the Megacities Carbon Project, future work includes incorporation into atmospheric CO$_2$

756   inversion research to further evaluate the Hestia-LA data product and improve estimation. Policymakers can use the

757   Hestia-LA results to better-understand FFCO$_2$ emissions at the human scale, offering the potential for improved

758   targeting of FFCO$_2$ reduction policy instruments. Finally, urban researchers can use Hestia-LA to explore a number

759   of important urban science questions such as how emissions intersect with other urban sociodemographic variables

760   such as income, education, housing size, or vehicle ownership.

761   The Hestia-LA data product is publicly available and will be updated with future years as data becomes available.

762   **Competing Interests.** The authors declare that they have no conflict of interest.

References

Ainsworth, M. (2014) Shapefile with AAWT data. Retrieved by personal communication from Mike Ainsworth (AINSWORT@scag.ca.gov) and Cheryl Leising (leising@scag.ca.gov) at Transportation Planning Department, SCAG Riverside Office.

AirNav.com. Data retrieved from: http://www.airnav.com/airports/ (Aug 1, 2018).

Alexis, A. (2011), Marine Emissions Model, California Air Resources Board. personal communication with Andy Alexis, July 6, 2011 (email: aalexis@arb.ca.gov). Retrieved from: https://www.arb.ca.gov/ports/marinevess/ogv/ogv1085.htm

Bréon, FM, Broquet, G, Puygrenier, V, Chevallier, F, Xueref-Remy, I, et al. 2015 An attempt at estimat- ing Paris area CO_2 emissions from atmospheric concentration measurements, *Atmos. Chem. Phys.*, **15**: 1707–1724. http://www.atmos-chem-phys. net/15/1707/2015/, DOI: https://doi.org/10.5194/ acp-15-1707-2015

Cambaliza, M. O. L., Shepson, P. B., Caulton, D. R., Stirm, B., Samarov, D., Gurney, K. R., Turnbull, J., Davis, K. J., Possolo, A., Karion, A., Sweeney, C., Moser, B., Hendricks, A., Lauvaux, T., Mays, K., Whetstone, J., Huang, J., Razlivanov, I., Miles, N. L. and Richardson, S. J.: Assessment of uncertainties of an aircraft-based mass balance approach for quantifying urban greenhouse gas emissions, Atmos. Chem. Phys., 14(17), 9029–9050, doi:10.5194/acp-14-9029-2014, 2014.

Cambaliza, M. O. L., Shepson, P. B., Bogner, J., Caulton, D. R., Stirm, B., Sweeney, C., Montzka, S. a., Gurney, K. R., Spokas, K., Salmon, O. E., Lavoie, T. N., Hendricks, A., Mays, K., Turnbull, J., Miller, B. R., Lauvaux, T., Davis, K., Karion, A., Moser, B., Miller, C., Obermeyer, C., Whetstone, J., Prasad, K., Miles, N. and Richardson, S.: Quantification and source apportionment of the methane emission flux from the city of Indianapolis, *Elem. Sci. Anthr.*, 3, 37, doi:10.12952/journal.elementa.000037, 2015.

California Air Resources Board (2014) *EMFAC2014 Volume I – User's Guide*, v1.0.7, April 30, 2014, California Environmental Protection Agency Air Resources Board, Mobile Source Analysis Branch, Air Quality Planning & Science Division. EMFAC data retrieved from: https://www.arb.ca.gov/emfac/2014/

California Energy Commission (2006) California Commercial End-Use Survey, CEC-400-2006-005. Retrieved from: http://www.energy.ca.gov/ceus/2006_enduse.html (Aug 1, 2018).

Carranza, V., T. Rafiq, I. Frausto-Vicencio, F.M. Hopkins, K.R. Verhulst, P. Rao, R.M. Duren, C.E. Miller (2018) Vista-LA: Mapping methane-emitting infrastructure in the Los Angeles megacity, Earth Syst., Sci. Data, 10, 653-676, https://doi.org/10.5194/essd-10-653-2018.

Chavez, A., and A. Ramaswami, 2011: Progress toward low carbon cities: Approaches for transboundary GHG emissions' footprinting. *Carbon Management*, **2**(4), 471-482, doi: 10.4155/cmt.11.38.

Christen, A., 2014: Atmospheric measurement techniques to quantify greenhouse gas emissions from cities. *Urban Climate*, **10**, 241-260, doi: 10.1016/j.uclim.2014.04.006.

Clark, S. S., and M. V. Chester, 2017: A hybrid approach for assessing the multi-scale impacts of urban resource use: Transportation in Phoenix, Arizona. *Journal of Industrial Ecology*, **21**(1), 136-150, doi: 10.1111/jiec.12422.

804   Commercial Building Energy Consumption Survey (2016) 2012 CBECS microdata files and information, U.S.
805   Energy Information Administration. Data retrieved from:
806   https://www.eia.gov/consumption/commercial/data/2012/index.php?view=microdata (Aug 1, 2018).
807   Davis, K.J., A. Deng, T. Lauvaux, N.L. Miles, S.J. Richardson, D. Sarmiento, K.R. Gurney, R.M. Hardesty, A.
808   Brewer, P.B. Shepson, M.O. Cambaliza, C. Sweeney, J. Turnbull, J. Whetstone, A. Karion (2017) The
809   Indianapolis Flux Experiment (INFLUX): A test-bed for developing anthropogenic greenhouse gas
810   measurements, *Elem Sci Anth*, **5**(21), https://www.elementascience.org/article/10.1525/elementa.188/
811   Department of Energy/Energy Information Administration 2003 Electric Power Monthly March 2003 Energy
812   Information Administration, Office of Coal, Nuclear, and Alternate Fuels, US Department of Energy,
813   Washington D.C. 20585. DOE/EIA form 923 reporting data retrieved from:
814   http://www.eia.gov/electricity/data/eia923 (July 27, 2018).
815   Department of Energy/Energy Information Administration (2018) State Energy Consumption Estimates 1960
816   through 2016, DOE/EIA-0214(2016), June 2018, Washington DC.
817   Djuricin, S., D. E. Pataki, and X. Xu, 2010: A comparison of tracer methods for quantifying CO_2 sources in an urban
818   region. *Journal of Geophysical Research*, **115**(D11), doi: 10.1029/2009jd012236.
819   Federal Aviation Administration (2018a), OPSNET Manual: http://aspmhelp.faa.gov/index.php/OPSNET_Manual
820   (Aug 1, 2018). Data retrieved from: https://aspm.faa.gov/opsnet/sys/main.asp.
821   Federal Aviation Administration (2018b), ETMSC Manual: http://aspmhelp.faa.gov/index.php/ETMSC_Manual
822   (Aug 1, 2018). Data retrieved from: https://aspm.faa.gov/tfms/sys/main.asp (Aug 1, 2018).
823   Federal Emergency Management Agency (2017) HAZUS database. Retreived from:
824   https://www.fema.gov/summary-databases-hazus-multi-hazard (Aug 1, 2018).
825   Feng, S., Lauvaux, T., Newman, S., Rao, P., Ahmadov, R., Deng, A., Díaz-Isaac, L. I., Duren, R. M., Fischer, M. L.,
826   Gerbig, C., Gurney, K. R., Huang, J., Jeong, S., Li, Z., **Miller, C. E**., O'Keeffe, D., Patarasuk, R., Sander, S. P.,
827   Song, Y., Wong, K. W., and Yung, Y. L.: Los Angeles megacity: a high-resolution land–atmosphere modelling
828   system for urban CO_2 emissions, Atmos. Chem. Phys., 16, 9019-9045, doi:10.5194/acp-16-9019-2016, 2016.
829   Getis, A., & Ord, J. K. (1992). The analysis of spatial association by use of distance statistics. *Geographical*
830   *analysis*, *24*(3), 189-206.
831   Grimmond, C. S. B., T. S. King, F. D. Cropley, D. J. Nowak, and C. Souch, 2002: Local-scale fluxes of carbon
832   dioxide in urban environments: Methodological challenges and results from Chicago.
833   Gurney, K.R., D. Mendoza, Y. Zhou, M Fischer, S. de la Rue du Can, S. Geethakumar, C. Miller (2009) The Vulcan
834   Project: High resolution fossil fuel combustion CO_2 emissions fluxes for the United States, *Environ. Sci.*
835   *Technol.*, 43(14), 5535-5541, doi:10.1021/es900806c.
836   Gurney K R, Huang J and Coltin K 2014 Comment on quick, J C (2014) carbon dioxide emission tallies for 210 US
837   coal-fired power plants: a comparison of two accounting methods J. Air Waste Manage. Assoc. 64: 73–79 J. Air
838   Waste Manage. Assoc. 64 1215–7
839   Gurney, K.R., J. Huang and K. Coltin (2016) Bias present in US federal agency power plant CO_2 emissions data and
840   implications for the US clean power plan, *Env. Res. Lett.*, 11, 064005, doi: 10.1088/1748-9326/11/6/064005.

841   Gurney, K. R., J. Liang, R. Patarasuk, D. O'Keeffe, J. Huang, M. Hutchins, T. Lauvaux, J. C. Turnbull, and P. B.
842   Shepson, 2017: Reconciling the differences between a bottom-up and inverse-estimated FFCO₂ emissions
843   estimate in a large U.S. urban area. *Elementa: Science of the Anthropocene*, **5**, 44, doi: 10.1525/elementa.137.
844   Gurney, K.R., Liang, J, D.O. O'Keeffe, R. Patarasuk, M. Hutchins, J. Huang, P. Rao, and Y. Song (2018)
845   Comparison of Global Downscaled Versus Bottom-Up Fossil Fuel CO₂ Emissions at the Urban Scale in Four
846   US Urban Areas, *under review at J. Geophys. Res.-Atmos.*
847   Gurney, K.R., J. Liang, D. O'Keeffe, J. Huang, Y. Song, P. Rao, T.M. Wong (2019), Hestia Fossil Fuel Carbon
848   Dioxide (FFCO₂) Data Product - Los Angeles Basin, Version 2.5, 1km grid,
849   https://doi.org/10.18434/T4/1502503 (last accessed December 20, 2018).
850   Heimberger Heimburger, AMF, Shepson, PB, Stirm, BH, Susdorf, C, Turnbull, J, et al. 2017 Precision Assessment
851   for the Aircraft Mass Balance Method for Measurement of Urban Greenhouse Gas Emission Rates. *Elem Sci*
852   *Anth*: In press for the INFLUX Special Feature
853   Hirsch, J. & Associates (2004) *Energy Simulation Training for Design & Construction Professionals*. Retrieved
854   from: http://doe2.com/download/equest/eQuestTrainingWorkbook.pdf (Aug 1, 2018). eQuest model download
855   available from: http://www.doe2.com/eQuest/ (Aug 1, 2018).
856   Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., Herold, N.D., Wickham, J.D.,
857   and Megown, K., 2015, Completion of the 2011 National Land Cover Database for the conterminous United
858   States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote*
859   *Sensing*, v. 81, no. 5, p. 345-354
860   Hopkins, F. M., Kort, E. A., Bush, S. E., Ehleringer, J., Lai, C., Blake, D., and Randerson, J. T.: Spatial pat- terns
861   and source attribution of urban methane in the Los Angeles Megacity, J. Geophys. Res.-Atmos., 121, 2490–
862   2507, https://doi.org/10.1002/2015JD024429, 2016b
863   Hutyra, L. R., R. Duren, K. R. Gurney, N. Grimm, E. A. Kort, E. Larson, and G. Shrestha, 2014: Urbanization and
864   the carbon cycle: Current capabilities and research outlook from the natural sciences perspective. *Earth's*
865   *Future*, **2**(10), 473-495, doi: 10.1002/2014ef000255.
866   Intergovernmental Panel on Climate Change "IPCC guidelines for national greenhouse gas inventories, Prepared by
867   the National Greenhouse Gas Inventories Programme" (IGES, Japan, 2006).
868   Jones, C., and D. M. Kammen, 2014: Spatial distribution of U.S. household carbon footprints reveals
869   suburbanization undermines greenhouse gas benefits of urban population density. *Environmental Science and*
870   *Technology*, **48**(2), 895-902, doi: 10.1021/es4034364.
871   Kort, E. A., C. Frankenberg, C. E. Miller, and T. Oda, 2012: Space-based observations of megacity carbon dioxide.
872   *Geophysical Research Letters*, **39**(17), doi: 10.1029/2012gl052738.
873   Lauvaux, T, Miles, NL, Richardson, SJ, Deng, A, Stauffer, D, et al. 2013 Urban emissions of CO₂ from Davos,
874   Switzerland: the first real-time moni- toring system using an atmospheric inversion tech- nique. *J. Appl Meteor.*
875   *and Climatol.*, **52**: 2654–2668. DOI: https://doi.org/10.1175/JAMC-D-13-038.1
876   Lauvaux, T., Miles, N. L., Deng, A., Richardson, S. J., Cambaliza, M. O., Davis, K. J., Gaudet, B., Gurney, K. R.,
877   Huang, J., O'Keefe, D., Song, Y., Karion, A., Oda, T., Patarasuk, R., Razlivanov, I., Sarmiento, D., Shepson, P.,
878   Sweeney, C., Turnbull, J. and Wu, K.: High-resolution atmospheric inversion of urban CO2 emissions during

879   the dormant season of the Indianapolis Flux Experiment (INFLUX), J. Geophys. Res. Atmos., 121(10), 5213–
880   5236, doi:10.1002/2015JD024473, 2016.

881   Le Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A. C., Korsbakken, J. I., Peters, G.
882   P., Canadell, J. G., Jackson, R. B., Boden, T. A., Tans, P. P., Andrews, O. D., Arora, V. K., Bakker, D. C. E.,
883   Barbero, L., Becker, M., Betts, R. A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Cosca, C. E., Cross, J.,
884   Currie, K., Gasser, T., Harris, I., Hauck, J., Haverd, V., Houghton, R. A., Hunt, C. W., Hurtt, G., Ilyina, T., Jain,
885   A. K., Kato, E., Kautz, M., Keeling, R. F., Klein Goldewijk, K., Körtzinger, A., Landschützer, P., Lefèvre, N.,
886   Lenton, A., Lienert, S., Lima, I., Lombardozzi, D., Metzl, N., Millero, F., Monteiro, P. M. S., Munro, D. R.,
887   Nabel, J. E. M. S., Nakaoka, S.-I., Nojiri, Y., Padin, X. A., Peregon, A., Pfeil, B., Pierrot, D., Poulter, B.,
888   Rehder, G., Reimer, J., Rödenbeck, C., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B. D., Tian, H.,
889   Tilbrook, B., Tubiello, F. N., van der Laan-Luijkx, I. T., van der Werf, G. R., van Heuven, S., Viovy, N.,
890   Vuichard, N., Walker, A. P., Watson, A. J., Wiltshire, A. J., Zaehle, S., and Zhu, D.: Global Carbon Budget
891   2017, Earth Syst. Sci. Data, 10, 405-448, https://doi.org/10.5194/essd-10-405-2018, 2018.

892   Lin, JC, Mitchell, M, Buchert, E, Crosman, E, Mendoza, D, Gurney, K, Patasuruk, R, Bowling, D, Pataki, D, Bares,
893   R, Fasoli, B, Catherine, D, Baasandorj, M, Jacques, A, Hoch, S, Horel, J, and Ehleringer, J 2018 CO_2 and
894   carbon emissions from cities: linkages to air quality, socioeconomic activity and stakeholders in the Salt Lake
895   City urban area, *Bull Am. Meteorological Soc.*, in review.

896   Los Angeles County (2016) Countywide Building Outlines – 2014 Update – Public Domain Release. Retrieved
897   from: https://egis3.lacounty.gov/dataportal/2016/11/03/countywide-building-outlines-2014-update-public-
898   domain-release/ (Aug 1, 2018).

899   Los Angeles World Airports (2014), Personal communication: Norene Hastings, Environmental Supervisor, Los
900   Angeles World Airports, Environmental Services division, January 2014.

901   Manufacturing Energy Consumption Survey (2010) 2010 MECS Survey Data, U.S. Energy Information
902   Administration. Retrieved from: https://www.eia.gov/consumption/manufacturing/data/2010/#r10 (Aug 1,
903   2018).

904   Martin, C.R., N Zeng, A. Karion, K. Mueller, S. Ghosh, I. Lopez-Coto, K.R. Gurney, T. Oda, K. Prasad, Y. Liu,
905   R.R. Dickerson, J. Whetstone (2018), Investigating Sources of Variability and Error in Simulations of Carbon
906   Dioxide in an Urban Region, *submitted to Atmospheric Environment*.

907   Mays, KL, Shepson, PB, Stirm, BH, Karion, A, Sweeney, C, et al. 2009 Aircraft-Based Measure- ments of the
908   Carbon Footprint of Indianapolis. *Envi- ronmental Science & Technology,* **43**(20): 7816–7823. DOI:
909   https://doi.org/10.1021/es901326b

910   McKain, K., A. Down, S. M. Raciti, J. Budney, L. R. Hutyra, C. Floerchinger, S. C. Herndon, T. Nehrkorn, M. S.
911   Zahniser, R. B. Jackson, N. Phillips, and S. C. Wofsy, 2015: Methane emissions from natural gas infrastructure
912   and use in the urban region of Boston, Massachusetts. *Proceedings of the National Academy of Sciences USA*,
913   **112**(7), 1941-1946, doi: 10.1073/pnas.1416261112.

914   Menzer, O., W. Meiring, P. C. Kyriakidis, and J. P. McFadden, 2015: Annual sums of carbon dioxide exchange over
915   a heterogeneous urban landscape through machine learning based gap-filling. *Atmospheric Environment*, **101**,
916   312-327, doi: 10.1016/j.atmosenv.2014.11.006.

917   Miles, NL, Richardson, SJ, Lauvaux, T, Davis, KJ, Deng, A, et al. 2017a Quantification of urban atmospheric
918   boundary layer greenhouse gas dry mole fraction enhancements: Results from the Indianapolis Flux Experiment
919   (INFLUX), *Elem Sci Anth*: In press for the INFLUX Special Feature.

920   Mitchell, L., J.C. Lin, D.R. Bowling, D.E. Pataki, C. Strong, A.J. Schauer, R. Bares, S.E. Bush, B.B. Stephens, D.
921   Mendoza, D. Mallia, L. Holland, K.R. Gurney, J.R. Ehleringer (2018) Long-term urban carbon dioxide
922   observations reveal spatial and temporal dynamics related to urban characteristics and growth, *Proceedings of*
923   *the National Academy of Sciences*. March 5, 2018, https://doi.org/10.1073/pnas.1702393115

924   Mount, D.M. and S. Arya (2010) ANN: A Library for Approximate Nearest Neighbor Searching, Version 1.1.2,
925   Release Date: Jan 27, 2010. Retrieved from: https://www.cs.umd.edu/~mount/ANN/ (Aug 1, 2018).

926   Newman, S., Xu, X., Gurney, K. R., Hsu, Y. K., Li, K. F., Jiang, X., Keeling, R., Feng, S., O'Keefe, D., Patarasuk,
927   R., Wong, K. W., Rao, P., Fischer, M. L., and Yung, Y. L.: Toward consis- tency between trends in bottom-up
928   CO_2 emissions and top-down atmospheric measurements in the Los Angeles megacity, At- mos. Chem. Phys.,
929   16, 3843–3863, https://doi.org/10.5194/acp- 16-3843-2016, 2016.

930   Patarasuk, R., Gurney, K. R., O'Keeffe, D., Song, Y., Huang, J., Rao, P., Buchert, M., Lin, J. C., Mendoza, D., and
931   Ehleringer, J. R.: Urban high-resolution fossil fuel CO_2 emis- sions quantification and exploration of emission
932   drivers for potential policy applications, Urban Ecosyst., 19, 1013–1039, https://doi.org/10.1007/s11252-016-
933   0553-1, 2016.

934   Porse, E., J. Derenski, H. Gustafson, Z. Elizabeth, and S. Pincetl, 2016: Structural, geographic, and social factors in
935   urban building energy use: Analysis of aggregated account-level consumption data in a megacity. *Energy*
936   *Policy*, **96**, 179-192, doi: 10.1016/j.enpol.2016.06.002.

937   Portland Cement Company, Economic Research Department (2006) *U.S. and Canadian Portland Cement Industry*
938   *Plant Information Summary*, Portland Cement Association, Skokie, IL.

939   Quick J 2014 Carbon dioxide emission tallies for 210 US coal- fired power plants: a comparison of two accounting
940   methods J. Air Waste Manage. Assoc. 64 73–9

941   Performance Measurement System (PeMS) Data Source: http://www.dot.ca.gov/trafficops/mpr/source.html (Aug 1,
942   2018).

943   Ramaswami, A., T. Hillman, B. Janson, M. Reiner, and G. Thomas, 2008: A demand-centered, hybrid life-cycle
944   methodology for city-scale greenhouse gas inventories. *Environmental Science and Technology*, **42**(17), 6455-
945   6461, doi: 10.1021/es702992q.

946   Rao, P., Gurney, K. R., Patarasuk, R., Yang, S., Miller, C. E., Duren, R. M., and Eldering, A.: Spatio-temporal
947   variations in on-road CO_2 emissions in the Los Angeles Megacity, AIMS Geosci., 3, 239–267,
948   https://doi.org/10.3934/geosci.2017.2.239, 2017.

949   Residential Energy Consumption Survey (2013) 2009 RECS Survey Data, U.S. Energy Information Administration.
950   Retrieved from: https://www.eia.gov/consumption/residential/data/2009/index.php?view=microdata (Aug 1,
951   2018).

952   Richardson Richardson, SJ, Miles, NL, Davis, KJ, Lauvaux, T, Martins, D, et al. 2017 CO_2, CO, and CH_4 surface in
953   situ measurement network in support of the Indianapolis FLUX (INFLUX) Experiment. *Elem Sci Anth*: Under
954   review for the INFLUX Special Feature.

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955   Schwandner et al.

956   Seto, KC, Dhakal, S, Bigio, A, Blanco, H, Delgado, GC, et al. 2014 Human Settlements, Infrastructure and Spatial

957   Planning. In: *Climate Change 2014: Mitigation of Climate Change*. Contribution of Working Group III to the

958   Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O, Pichs-Madruga, R,

959   Sokona, Y, Farahani, E, Kadner, S, Seyboth, K, Adler, A, Baum, I, Brunner, S, Eickemeier, P, Kriemann, B,

960   Savolainen, J, Schlömer, S, von Stechow, C, Zwickel, T and Minx, JC (eds.)]. Cambridge University Press,

961   Cambridge, United Kingdom and New York, NY, US.

962   Shu, Y., and N. S. N. Lam, 2011: Spatial disaggregation of carbon dioxide emissions from road traffic based on

963   multiple linear regression model. *Atmospheric Environment*, **45**(3), 634-640, doi:

964   10.1016/j.atmosenv.2010.10.037.

965   Southern California Association of Governments (2012) Parcel Data GIS Shapefiles. Retrieved by personal

966   communication from Kimberly S. Clark (Clark@scag.ca.gov) and Christine Fernandez

967   (fernandez@scag.ca.gov).

968   Southern California Association of Governments (2014) SCAG AWDT data, personal communication, Mike

969   Ainsworth (AINSWORT@scag.ca.gov), Transportation Modeling, Air Quality & Conformity, October, 2014.

970   Turnbull, J. C., Sweeney, C., Karion, A., Newberger, T., Lehman, S. J., Tans, P. P., Davis, K. J., Lauvaux, T., Miles,

971   N. L., Richardson, S. J., Cambaliza, M. O., Shepson, P. B., Gurney, K., Patarasuk, R. and Razlivanov, I.:

972   Toward quantification and source sector identification of fossil fuel CO2 emissions from an urban area: Results

973   from the INFLUX experiment, J. Geophys. Res. Atmos., 120(1), 292–312, doi:10.1002/2014JD022555, 2015.

974   United States Environmental Protection Agency (1995) FIRE Version 5.0 Source Classification Codes and Emission

975   Factor Listing for Criteria Ai Pollutants, EPA-454/R-95-012. Retrieved from

976   https://www3.epa.gov/ttn/chief/old/efdocs/454r95012.pdf (July 27, 2018).

977   United States Environmental Protection Agency (2013) Facility Registry Service (FRS). Setting Up A Data Flow

978   with FRS: FRS Information Needs. Retrieved from https://www.epa.gov/frs/setting-data-flow-frs-frs-

979   information-needs (Aug 1, 2018).

980   United States Environmental Protection Agency (2014a), Motor Vehicle Emission Simulator (MOVES) User Guide

981   for MOVES2014, EPA-420-B-14-055. Retrieved from https://www.epa.gov/moves/moves2014a-latest-version-

982   motor-vehicle-emission-simulator-moves (July 27, 2018).

983   United States Environmental Protection Agency (2015a) Technical Support Document (TSD) Preparation of

984   Emissions Inventories for the Version 6.2, 2011 Emissions Modeling Platform. Retrieved from

985   https://www.epa.gov/air-emissions-modeling/2011-version-62-technical-support-document (July 27, 2018).

986   United States Environmental Protection Agency (2015b) 2011 National Emissions Inventory, version 2 Technical

987   Support Document. Document retrieved from https://www.epa.gov/air-emissions-inventories/2011-national-

988   emissions-inventory-nei-technical-support-document (July 27, 2018). NEI version 2.0 data retrieved from:

989   https://www.epa.gov/air-emissions-inventories/2011-national-emissions-inventory-nei-data (July 27, 2018).

990   United States Environmental Protection Agency (2015c) 40 DFR Part 60, EPA-HQ-OAR-2013-0602; FRL-XXXX-

991   XX-OAR, RIN 2060-AR33, Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric

992   Utility Generating Units, August 3, 2015. Air Markets Program Data 2012 Pre-packaged data retrieved from:

993   ftp://ftp.epa.gov/dmdnload/emissions/hourly/monthly/ (May 28, 2012).

994   USGS (2003) *Minerals Yearbook, Vol. 1, Metals and Minerals, 2002*. U.S. Geological Survey. U.S. Department of
995   the Interior. July 2003

996   VandeWeghe, J. R., and C. Kennedy, 2007: A spatial analysis of residential greenhouse gas emissions in the
997   Toronto census metropolitan area. *Journal of Industrial Ecology*, **11**(2), 133-144, doi: 10.1162/jie.2007.1220.

998   Velasco, E., and M. Roth, 2010: Cities as net sources of CO_2: Review of atmospheric CO_2 exchange in urban
999   environments measured by eddy covariance technique. *Geography Compass*, **4**(9), 1238-1259, doi:
1000   10.1111/j.1749-8198.2010.00384.x.

1001   Velasco, E., S. Pressley, E. Allwine, H. Westberg, and B. Lamb, 2005: Measurements of CO_2 fluxes from the
1002   Mexico City urban landscape. *Atmospheric Environment*, **39**(38), 7433-7446, doi:
1003   10.1016/j.atmosenv.2005.08.038.

1004   Verhulst, K. R., Karion, A., Kim, J., Salameh, P. K., Keeling, R. F., Newman, S., Miller, J., Sloop, C., Pongetti, T.,
1005   Rao, P., Wong, C., Hopkins, F. M., Yadav, V., Weiss, R. F., Duren, R. M., and Miller, C. E.: Carbon dioxide
1006   and methane measurements from the Los Angeles Megacity Carbon Project – Part 1: calibration, urban en-
1007   hancements, and uncertainty estimates, Atmos. Chem. Phys., 17, 8313–8341, https://doi.org/10.5194/acp-17-
1008   8313-2017, 2017

1009   Whetstone, J.R. (2018) Advances in urban greenhouse gas flux quantification: The Indianapolis Flux Experiment
1010   (INFLUX). Elem Sci Anth, 6: 24. DOI: https://doi.org/10.1525/elementa.282

1011   Wong, C. K., Pongetti, T. J., Oda, T., Rao, P., Gurney, K. R., New- man, S., Duren, R. M., Miller, C. E., Yung, Y.
1012   L., and Sander, S. P.: Monthly trends of methane emissions in Los Angeles from 2011 to 2015 inferred by
1013   CLARS-FTS observations, Atmos. Chem. Phys., 16, 13121–13130, https://doi.org/10.5194/acp-16- 13121-
1014   2016, 2016.

1015   Wong, K. W., Fu, D., Pongetti, T. J., Newman, S., Kort, E. A., Duren, R., Hsu, Y.-K., Miller, C. E., Yung, Y. L.,
1016   and Sander, S. P.: Mapping $CH_4 : CO_2$ ratios in Los Angeles with CLARS- FTS from Mount Wilson,
1017   California, Atmos. Chem. Phys., 15, 241–252, https://doi.org/10.5194/acp-15-241-2015, 2015

1018   Wu, K, Lauvaux, T, Davis, KJ, Deng, A, Lopez Coto, I, Gurney, KR and Patarasuk, R 2018 Joint inverse estimation
1019   of fossil fuel and biogenic CO_2 fluxes in an urban environment: An observing system simulation experiment to
1020   assess the impact of multiple uncertainties. *Elem Sci Anth.* DOI: http:// doi.org/10.1525/elementa.138

1021   Wunch, D., Wennberg, P. O., Toon, G. C., Keppel-Aleks, G., and Yavin, Y. G.: Emissions of greenhouse gases from
1022   a North American megacity, Geophys. Res. Lett., 36, 1–5, https://doi.org/10.1029/2009GL039825, 2009.

1023   Zhou, Y. Y., and K. R. Gurney, 2011: Spatial relationships of sector-specific fossil fuel CO_2 emissions in the United
1024   States. *Global Biogeochemical Cycles*, **25**, GB3002, doi: 10.1029/2010gb003822.