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Quantification of Fossil Fuel CO_2 Emissions on the Building/Street Scale for a Large U.S. City

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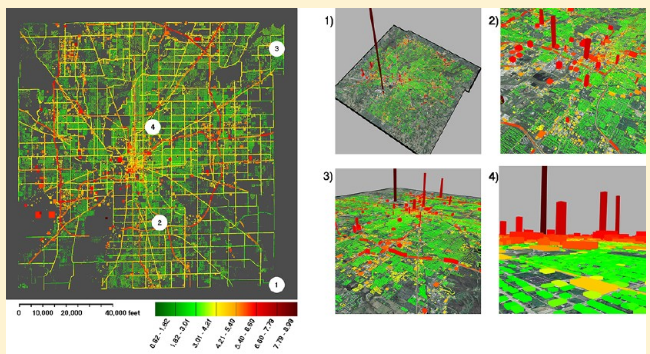
S Supporting Information

ABSTRACT: In order to advance the scientific understanding of carbon exchange with the land surface, build an effective carbon monitoring system, and contribute to quantitatively based U.S. climate change policy interests, fine spatial and temporal quantification of fossil fuel CO_2 emissions, the primary greenhouse gas, is essential. Called the "Hestia Project", this research effort is the first to use bottom-up methods to quantify all fossil fuel CO_2 emissions down to the scale of individual buildings, road segments, and industrial/electricity production facilities on an hourly basis for an entire urban landscape. Here, we describe the methods used to quantify the on-site fossil fuel CO_2 emissions across the city of Indianapolis, IN. This effort combines a series of data sets and simulation tools such as a building energy simulation model, traffic data, power production reporting, and local air pollution reporting. The system is general enough to be applied to any large U.S. city and holds tremendous potential as a key component of a carbon-monitoring system in addition to enabling efficient greenhouse gas mitigation and planning. We compare the natural gas component of our fossil fuel CO_2 emissions estimate to consumption data provided by the local gas utility. At the zip code level, we achieve a bias-adjusted Pearson r correlation value of 0.92 ($p < 0.001$).



INTRODUCTION

Carbon dioxide (CO_2) emissions from fossil fuel combustion are the largest net annual flux of carbon to the atmosphere and represent the dominant source of greenhouse gas forcing.[1,2] Fossil fuel CO_2 emissions are often used as a near-certain boundary condition when solving total carbon budgets, an endeavor essential to quantifying other components of the carbon cycle and to improving our understanding of the feedbacks between the carbon cycle and climate change.[3] Similarly, in order to construct meaningful projections of greenhouse gas emissions, a mechanistically based quantification of current emissions is necessary. Finally, greenhouse gas mitigation efforts require improved quantification of fluxes in order to establish emission baselines, verify emission trajectories, and for the identification of efficient, economically viable mitigation options.[4]

An important attribute of fossil fuel CO_2 quantification is the space and time scale considered. A number of international and national agencies collect and report on emissions at the national and global scales and most commonly at annual time steps.[5] Spatial proxies have been commonly used to quantify spatial distribution of globally comprehensive emissions at the subnational scales.[6−9] Regional efforts at subnational quantification have also been accomplished, often relying on a mixture of space and time proxies in addition to bottom-up data such as pollution emissions and fuel consumption statistics.[10−13]

However, recently emerging scientific and decision support needs require another step in emissions resolution down to the scale of the urban landscape. The density of atmospheric measurements of CO_2 and its isotopic signature are increasing, and the measurement network is becoming multitiered, including satellite, aircraft, flux tower, and surface air sampling.[14−16] The increasing density is offering the opportunity to better understand the mechanisms driving land−atmosphere carbon exchange that occur at the scale of a forest plot or urban road segment. The ability to measure atmospheric CO_2 and its isotopic signature at scales that might isolate fossil fuel emissions from the biological exchange, in addition to discernment of discrete entities such as power plants and roadways, requires us to also build emissions estimates from the "bottom up" through higher resolution source quantifica-

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tion.[17,18] Furthermore, construction of higher resolution, mechanistically based fossil fuel CO_2 emission estimation assists in better quantification and understanding of other pollutants such as CO and black carbon.[19]

These atmospheric/inventory measurement and model needs are driven, in part, by monitoring, reporting, and verification (MRV) requirements that are emerging or anticipated to emerge at local, national, and international levels.[20−23] Similarly important are information needs to plan and optimize fossil fuel CO_2 mitigation strategies. For example, should emissions mitigation policy such as a cap-and-trade system become law, initial allocations and mitigation targets will be established.[24] In order to meet such mitigation targets, action will be taken at local levels where industry functions, consumers live, and power is produced. It is at these scales that quantitative information on emissions baselines and mitigation options are most readily needed, and it is at the urban landscape scale that knowledge about local mitigation options, costs, and opportunities is the greatest.[25−29]

Focus on the urban domain is driven in no small part by the recognition that 51% of the world's population resided in cities in 2010 and that share is projected to grow to 68% by 2050.[30] Moreover, the rise of the megacity (over 10 million inhabitants) emphasizes the magnitude and trend toward global urbanization.[31] Hence, efforts to better understand the carbon cycle and its interaction with climate at the urban landscape scale offer an intellectual connection to the growing research on urban sustainability and urban metabolic systems.[32−34]

Current research aimed at quantifying fossil fuel CO_2 at the urban landscape scale typically stops at the level of the whole city or the census tract. For example, a number of studies have quantified fossil fuel CO_2 emissions on the scale of an entire county or city.[4,35−40] Other studies have attempted somewhat smaller spatial scales by quantifying emissions on the census tract or "community" level.[41] As yet, no peer-reviewed research has attempted comprehensive quantification of fossil fuel CO_2 emissions on the scales of individual buildings or neighborhoods for the entirety of an urban landscape.

In this study, called the "Hestia Project", we quantify all on-site fossil fuel CO_2 emissions at the building/road level every hour for the entire city of Indianapolis, IN. This study aims to establish an approach to quantify high-resolution on-site fossil fuel CO_2 emissions across an entire urban landscape that can be reproduced across the U.S. while quantitative linkages to a national-level greenhouse gas accounting system are maintained.[42] The method and results we describe here reflect the on-site fossil fuel combustion within the physical domain of the city, excluding upstream or life-cycle associated emissions. Hence, emissions associated with material consumed within but produced outside the city are not reflected in the emissions estimation, nor is electricity that is consumed within the city but generated outside of it. In the Methods section we describe the study area and the methods by which we quantify each emitting economic sector on the building/road spatial scale and hourly time scale. In the Results and Discussion section we provide results and discuss the drivers and the space and time patterns resulting from the estimation approach. We conclude with a comparison to independent data from the local natural gas utility.

■ METHODS

Indianapolis, IN, is the study area for the estimation approach described in this paper. Indianapolis is the county seat of Marion County, which has boundaries nearly identical to those of the city of Indianapolis. Since most of the original data sources are reported at the county level, we performed analysis for the Marion County domain, though the results are valid for either the county or city given their close spatial correspondence. The city contains nine townships: Pike, Washington, Lawrence, Wayne, Center, Warren, Decatur, Perry, and Franklin. The city is located on a flat plain and is relatively symmetrical, with growth extending in all directions. It is an "island" city in the sense that it is surrounded in all directions by rural land-use, primarily cropland. This makes both atmospheric monitoring and CO_2 inflow boundary questions more tractable as large upwind fossil fuel sources are well-mixed by the time they reach the Indianapolis area. As the capital of the state of Indiana, Indianapolis was listed as the 12th largest city in the U.S. in 2010 with a population of 820 445.[43]

The building/street level fossil fuel CO_2 quantification presented in this study starts with emissions quantification generated by the Vulcan Project in Marion County for the data-rich year 2002.[10,44] The Vulcan Project utilizes a number of data sets, including CO emissions from the National Emissions Inventory (NEI), direct CO_2 stack monitoring at the largest power plants, and on road activity data. These data and the methods employed in the Vulcan Project have been presented and described in detail elsewhere.[44] The methods used to generate the building/street level emissions presented here represent a downscaling effort and are best described within individual economic sectors. Table 1 provides the breakdown of the Vulcan fossil fuel CO_2 emissions for Marion County disaggregated by data source, sector, and fuel category. Two categories, in particular, require considerable downscaling effort to attain building/street level resolution. The first is buildings in which commercial, residential, or industrial activities occur. The second is the on road transportation.

Nonpoint Residential and Commercial Buildings. Fossil fuel CO_2 emissions associated with residential and commercial buildings in the city of Indianapolis reflect on-site combustion of fossil fuels only. Consumption of electricity and the associated emissions are located at the electricity generation location. The methodology employed for residential and commercial building emissions has been described in detail elsewhere.[45] However, some improvements and corrections have been made to the original approach, and those are described in Supporting Information text along with a summary of the overall nonpoint residential and commercial building emissions methodology (Supporting Information, text 1). In short, the nonpoint residential and commercial building emissions quantification allocates the Vulcan census tract totals into individual buildings based on the results of a building-level energy consumption model driven by building attribute information retrieved from the county assessor's building parcel (BP) data layer. The building energy model supplies a nonelectric energy-use intensity (NE-EUI) value that, when combined with the total floor area for each building, provides an estimate of nonelectric energy consumption. The values obtained from the building energy consumption model are not used in their absolute form, but they are relied upon for relative distribution among residential and commercial buildings in an individual economic sector, the total of which is constrained by the Vulcan system.

Industrial Nonpoint Buildings. Lacking classification for industrial buildings in the building energy consumption model used to quantify energy use within residential and commercial

Table 1. Fossil Fuel CO_2 Emissions Categorized by Data Source, Sector and Fuel for Marion County, IN, 2002 (units of Mt C/yr)

data source	monpoint NEI[a]									point NEI						point NEI/point CAMD[b]			NMIM NCD[c]		airport NEI
sector	industrial			commercial			residential			industrial			commercial			electricity production			transportation		airport
																			on road	non road	
fuel	coal	petrol	NG	coal	petrol	NG	coal	petrol	NG	coal	petrol	NG	coal	petrol	NG	coal	petrol	NG	petrol	petrol	petrol
emissions	0.10	0.05	0.19	0	0.06	0.27	0.004	0.009	0.35	0	0.017	0.092	0	0.003	0.018	1.0	0.008	0.030	1.07	0.13	0.17

[a]NEI refers to the United States Environmental Protection Agency National Emissions Inventory CO emissions reporting. See ref 10 for more information. [b]CAMD refers to the United States Environmental Protection Agency Clean Air Markets Division (Supporting Information, text 3). [c]NMIM NCD refers to the National Mobile Inventory Model National County Database (Supporting Information, text 4).

buildings and having limited information on industrial NE-EUI values, we estimated the nonpoint industrial buildings in Marion County using a different approach. Instead, we constructed carbon intensity values (mass of carbon emitted per unit floor area) from national statistics and combined this with the BP data layer to arrive at a building-by-building carbon emissions estimate.

Carbon intensity (CI) for industrial buildings was calculated by dividing national total annual CO_2 emissions by the national total building floor area within industrial subsectors classified according to the North American Industry Classification System (NAICS).[46−48] This required the 18 industrial building types in the BP data layer to be reclassified into the 10 NAICS industrial subsectors. Furthermore, buildings with natural gas service were assigned the natural gas emissions, while those without were assigned the coal- and petrol-based emissions. The temporal behavior of CO_2 emissions in each industrial building was estimated by using temporal profile data from the United States Environmental Protection Agency (EPA), which includes monthly, weekly, and diurnal patterns specific to Source Classification Codes (SCC).[49] A detailed description of the nonpoint industrial building fossil fuel CO_2 emissions is provided in the Supporting Information (text 2).

Industrial, Commercial, and Electricity Production Point Sources. The commercial and industrial sectors contain emissions emanating from point source pollution reporting. For the industrial sector, there are 144 facilities in Marion County reporting as point sources. In the commercial sector, there are 46 facilities. The CO_2 emissions calculated by the Vulcan Project at the geolocated points are transferred into the urban database constructed here. In the industrial sector, point sources account for 24% of the total industrial CO_2 emissions in Marion County. For the commercial sector the share is 6% (see Table 1).

The emissions from electricity production are primarily supplied by data obtained from the EPA Clean Air Market Division (CAMD) Emission Tracking System/Continuous Emissions Monitoring system (ETS/CEMs) for Electrical Generating Units (EGUs).[50,51] Within Marion County, three facilities report through the CAMD, and an additional seven facilities report through the National Emissions Inventory (NEI) source reporting due the small size of the facilities (Supporting Information, text 3).

Transportation. The transportation sector contains estimates for on road, non road, and air travel transportation. The non road (county scale) and air travel (point scale) subsectors are derived from the Vulcan estimate, and no additional downscaling in space or time is performed (Supporting Information, text 4). On road emissions from Vulcan are further downscaled into the urban landscape starting with the Marion County Vulcan estimate specific to month, vehicle type, and road type. The Vulcan emissions are based on a combination of county-level data from the National Mobile Inventory Model (NMIM) County Database (NCD) and standard internal combustion engine stoichiometry from the MOBILE6.2 combustion emissions model.[10] The Vulcan estimate provides on road CO_2 emissions for six road types (three urban and three rural) and 28 different vehicle classes. In order to distribute these county-level emissions in space, the geographic location of roads and the density of traffic flow were used and result in quantification of on road emissions by vehicle type, road type, and road segment every hour of the day (Supporting Information, text 4).

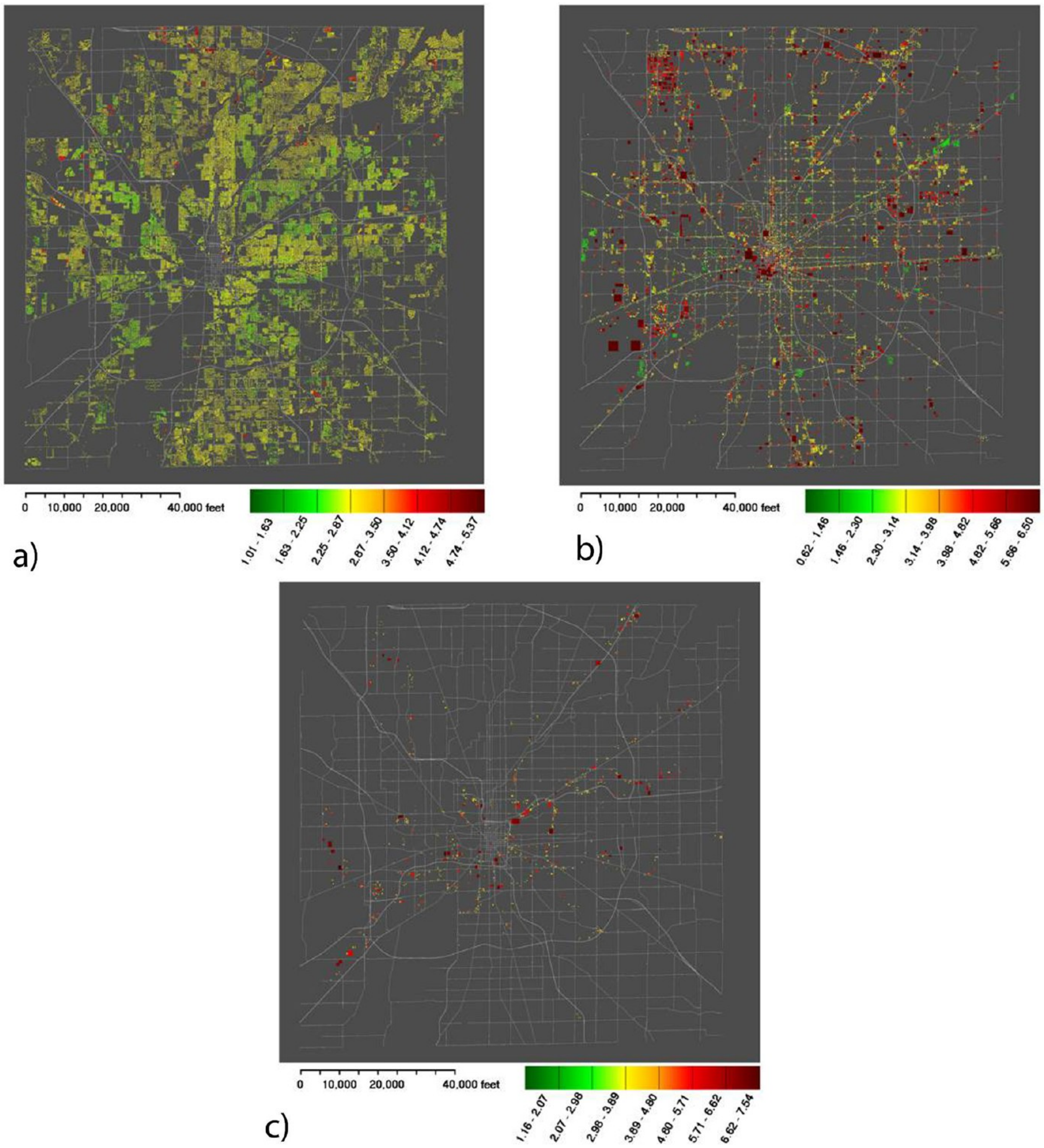


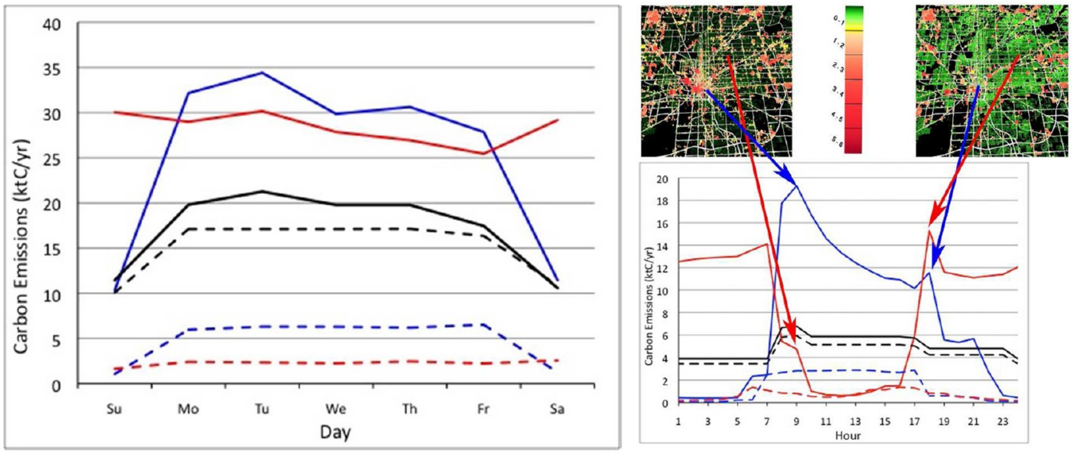
Figure 1. Annual fossil fuel CO_2 emissions for the (a) residential, (b) commercial, and (c) industrial sectors in Marion County, IN. Note the different scale in each panel. Units: $\log_{10}$ kg C/yr.

■ RESULTS AND DISCUSSION

Space and Time Patterns: Residential, Commercial, and Industrial. The spatial distribution of the residential, commercial, and industrial buildings is presented in Figure 1. In general, the city exhibits a development and land-use pattern reflective of circular outward growth from the older city center to the newer suburban and commercial hubs on the outer transportation artery. The residential sector shows residential clustering in the center portion of the city in addition to satellite clusters on the outer ring interstate highway that connects newer suburban areas to the city center. The commercial buildings cluster around major arterial intersection nodes on the outer ring interstate in addition to substantial commercial development in the city center.

The industrial sector buildings are more randomly clustered, though there is correspondence to the major "spoke" interstates emanating from the center of the city, particularly the interstate that runs in a SW–NE trajectory (I-70), which is a major coast-to-coast interstate.

Figure 2 shows the seasonal, weekly, and diurnal temporal structure of the residential, commercial, and industrial building emissions aggregated for the whole city. For the diurnal cycle, residential emissions are elevated from roughly 5 p.m. to 7 a.m. relative to the daytime hours. Peak emissions occur at 7 a.m. and 6 p.m., when residential activity is considered to be at a maximum (preparing for work/school, dinner/family activities). Commercial/industrial emissions, by contrast, have maximum values during the daylight working hours with peaks at roughly 9 a.m. and 6 p.m. The latter is due to the overlap of daytime work shifts and the evening or nighttime work shifts particularly common in the retail commercial sector (Figure 2b). The seasonality of the diurnal patterns show a straightforward scaling of the time profile. with winter values larger than summer values, due to greater space heating needs when outdoor temperatures are lower. The weekly time structures also exhibit both sectoral and seasonal differences. The industrial and commercial sectors exhibit weekend declines relative to weekday values and overall larger emissions during



a) b)

Figure 2. Seasonal fossil fuel CO_2 emissions for buildings in Indianapolis, IN. (a) Weekly temporal profiles for the residential, commercial, and industrial sectors; (b) diurnal temporal profiles for the residential, commercial, and industrial sectors. Key: industrial (black), commercial (blue), residential (red), summer (dashed), winter (solid). The insets in part b show commercial (downtown) and residential sectors at 9 a.m. and 6 p.m. Units: kt C/yr.

winter than summer. The residential sector, by contrast, shows slight increases on weekend days compared to weekend days. Both the seasonal diurnal and weekly time profiles are predominantly driven by a combination of the survey-based building "schedules" and the local external surface temperature statistics for Indianapolis in 2002.

Space and Time Patterns: On Road Transportation. The on road CO_2 emissions quantified for each road segment are presented in Figure 3. Due to the fact that Marion County

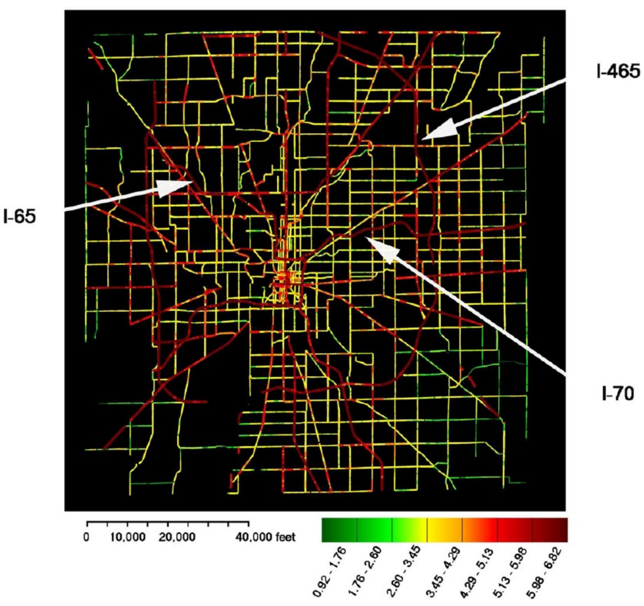


Figure 3. Annual on road CO_2 emissions for Marion County, 2002. Major interstates are noted. Units: $\log_{10}$ t C/yr.

is the center of the metropolitan area, most of the road types belong to the urban group. The source data contain no emissions for rural interstates and rural arterials, though there are nonzero road lengths in those categories.

Urban interstate and arterial roads comprise 15% of the total road length but 62% of total CO_2 emission due to the much greater traffic volume on these road types. Figure 4 demonstrates this as the large interstate that circles the city (I-465) and the two large interstates that bisect the city (I-65 and I-70) dominate emissions. Urban minor arterials and major collectors represent 9.4% of the total road length but nearly 22% of the total CO_2 emissions. By contrast, urban minor collectors and local roads represent 63% of the total road length but only 16% of the total CO_2 emission (Supporting Information, Table 6).

Among all the vehicle types (Supporting Information, Table 7), light-duty gasoline vehicles contribute the largest CO_2 emissions (489.9 kt C/year), with light-duty gasoline trucks (both 0−3750 and 3751−5750 lbs) being the next largest emitting vehicle type category (339.7 kt C/year). Overall, fossil fuel CO_2 emissions due to gasoline-fueled vehicles are 8 times larger than diesel-fueled emissions.

The diurnal cycle of on road CO_2 emissions displays a temporal structure defined by aggregate vehicle class and day of the week (Figure 4). During weekdays, the whole-city traffic for light-duty vehicles (passenger cars) shows maxima in the 6−9 a.m. and 3−8 p.m. time periods. The evening rush hour is of longer duration with a more gradual onset and decline than the morning rush hour. Heavy-duty vehicles show little to no rush hour pattern but remain elevated from roughly 6 a.m. to 5 p.m., after which they exhibit a gradual decline between 5 and 8 p.m. This is consistent with heavy-duty vehicles being engaged in primarily commercial travel (local and interstate) and, hence, being active throughout daytime hours.[52] Weekend traffic, by contrast, exhibits consistent emissions throughout daytime hours for both the light-duty and heavy-duty vehicle groups, with a long increase from 6 a.m. to roughly noon. The weekday nighttime emissions for light-duty vehicles is near-zero, whereas heavy-duty vehicles maintain small but nonzero emissions during this time, consistent with the presence of interstate commercial trucking. Interestingly, weekend light-duty vehicle emissions reach a minimum at roughly 4 a.m., staying somewhat elevated relative to weekday emissions in the late evening/early morning hours, consistent with greater social noncommercial activity on weekend nights.

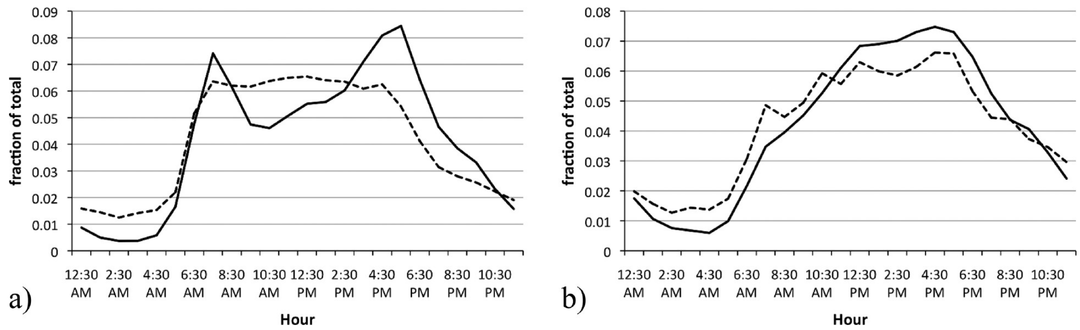


Figure 4. On road transportation annual mean diurnal fossil fuel CO_2 emissions hourly fraction for light-duty (solid) and heavy-duty (dashed) vehicle class aggregates: (a) weekday emissions and (b) weekend emissions. Units: fraction of daily total.

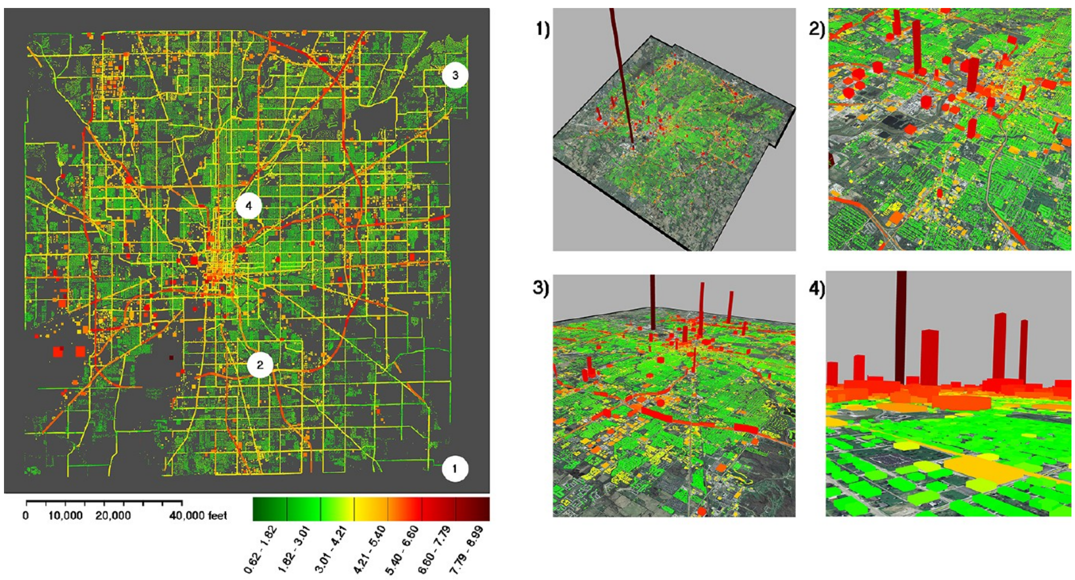


Figure 5. Total fossil fuel CO_2 emissions for Marion County, IN, for the year 2002: (a) top view with numbered zones and (b) blowups of the numbered zones. Color units: $\log_{10}$ kg C/yr. Box height units: linear.

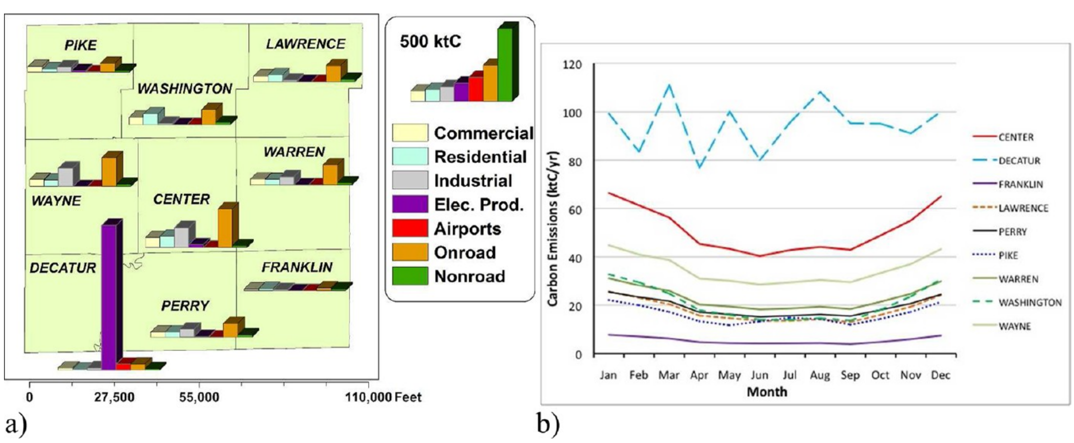


Figure 6. 2002 Fossil fuel CO_2 emissions for Marion County, IN: (a) by sector for the nine townships and (b) monthly profile by township.

Space and Time Patterns: Total Emissions. Figure 5 presents the total fossil fuel CO_2 emissions for the city of Indianapolis. The large arterial roadways and general building patterns are the dominant features. Also shown is a 3D view of the downtown area showing the dominance of Harding St. Station, a 1996 MW nameplate capacity power plant.

Figure 6 presents the distribution of fossil fuel CO_2 emissions by economic sector, township, and month (Supporting Information, text 5). Marion County includes nine townships of near equal geography but varying population and commercial/industrial activity. Decatur Township, with the largest overall fossil fuel CO_2 emissions, contains the Harding St. Station power generation facility. Decatur Township is also

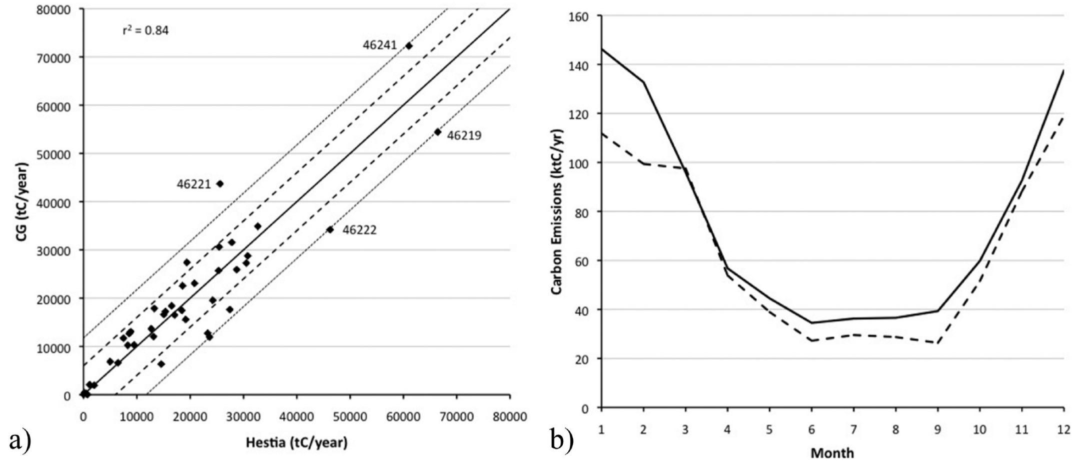


Figure 7. Comparison of the summed residential, commercial, and industrial building CO_2 emissions from Citizen's Gas versus this study due to natural gas consumption in Marion County. (a) Annual zip code comparison. Hestia values have been bias-adjusted. Also shown: 1:1 line (solid), one standard deviation (dashed), two standard deviations (dotted). Outlier zip codes are noted. (b) Monthly, county-total comparison: this study (solid), Citizen's Gas (dashed). No bias adjustment was made.

home to the Indianapolis International Airport. These account for the large electricity production and airport emissions, respectively. The remaining seven townships have on road emissions as their largest emitting sector, with industrial activity notable in Wayne and Center Townships. The seasonal profile of the fossil fuel emissions follows a similar winter/summer pattern, with Decatur township reflecting the electricity production variations of the Harding St. Power Station.

Comparison to Natural Gas Consumption Data. Independent data on natural gas consumption was acquired from Citizen's Gas (CG), the local natural gas utility in Indianapolis serving Marion County. The data supplied by CG was disaggregated to zip code for the year 2009 and as monthly county totals for the years 2000−2009. In order to compare the results presented here to the CG data, the fractional values in each zip code for the year 2009 were transferred to the year 2002 total. Hence, actual changes in spatial distribution at scales larger than the zip code will generate differences in comparison to the Hestia estimate.

Figure 7 provides a comparison of the estimates generated in this study with the CG data. The county-total Hestia estimate is roughly 17% larger than the CG estimate. The Hestia uncertainty (2σ) associated with NG consumption is roughly 11%; hence, this represents a statistically significant difference. However, one source of uncertainty remains unquantified and may represent a bias to the Hestia county-total estimate. The county-total nonpoint emissions are based on state-level sales of natural gas allocated to the counties in Indiana on the basis of proxies such as number of households (residential sector), commercial employees (commercial sector), and manufacturing employees (industrial sector). The allocation by proxies could misrepresent the county apportionment across the state. Furthermore, there is anecdotal evidence that CG is not the only natural gas supplier in the county. More specifically, large industrial consumers may have individual contracts with natural gas suppliers. Hence, the CG estimate may not represent the true county-total NG consumption.

Figure 7a displays the comparison at the annual zip code level after removing the mean county-total difference between the Hestia and CG estimate. The explained variance is high (r^2 = 0.84), though five zip codes contain emissions that are greater than or equal to two standard deviations from the 1:1 line. The county-total monthly distribution similarly shows reasonable correspondence, with the total bias showing up primarily during January and February (Figure 7b).

Implications and Future Directions. The research presented here is now part of a larger experiment in which atmospheric concentrations of CO_2, CH_4, CO, and $\Delta^{14}CO_2$ are being measured from aircraft and ground-based instruments in and around Indianapolis. This experiment, called INFLUX, will constrain and define uncertainty in estimating carbon fluxes through improved measurement techniques, inverse modeling, and comparison to emissions data products. Comparison of a "top-down" approach to the "bottom-up" emissions estimation performed here will offer an important contraint to the Hestia system results. This will form the first step toward a carbon monitoring system that will ultimately combine satellite, airborne, and ground-based measurements with independent emissions estimation and nested atmospheric modeling to verify reported emission reductions.[18] Indeed, the space and time emissions detail has implications for the interpretation of ongoing INFLUX atmospheric CO_2 concentration measurements in and around Indianapolis, in addition to achieving a much improved a priori emissions footprint for atmospheric CO_2 inversions. In a "forward" mode, knowing the dominant upwind source distribution and its temporal variation can aid in interpreting measurement time series to best isolate the urban fossil fuel component from the background and biological CO_2 sources. In the "inverse" mode, a more accurate space/time-resolved prior flux estimate will lead to a more constrained inverse flux estimate. The latter purpose puts emphasis on the need to quantify uncertainty at the subcounty scale, something that has not been done but is anticipated.

High-resolution emissions quantification with functional detail can also aid in the decision making necessary to achieve lowest cost emission mitigation efforts. Knowing the quantities and spatial distribution of fossil fuel CO_2 emissions in a city allows for targeting areas with high-impact/low-cost solutions. For example, the emission mitigation impact of targeting older, less insulated homes can be quantified and compared to targeting zones of congested, high-emitting on road sources. Mitigation costs also have space and time dependence, and these can be convolved with emissions savings for optimal impact. Of course, as was noted previously, the direct combustion approach is not perfectly suited for mitigation analysis; allocation of the power plant emissions to the consumption point is crucial for a comprehensive policy framework.

Future work on the Hestia Project will emphasize a number of research avenues. Expansion to include quantification of CH_4 emissions is planned and is part of the INFLUX experiment. Estimation will likely rely on assumptions about leak rates from large gas pipeline junctions, landfills, and wastewater treatment. Calibration to independent observed data also remains challenging, particularly given the limited availability of utility consumption data. Voluntary collection of a stratified sample of energy consumption data could be one way to overcome this limitation. However, coordination, data reliability, and incentives to participate all pose difficulties.

Another avenue of future research is to link the Hestia system, focused on carbon emissions, to efforts aimed at quantifying the complete urban metabolism or uban life cycle. Urban metabolism research is typically focused on the consumption of energy and materials and their transformation and ultimate disposition in waste streams or goods. Linking these two approaches would require carbon emissions to be traced both upstream and downstream to the consumption activity driving the fossil fuel combustion.

■ ASSOCIATED CONTENT

Supporting Information

This information is available free of charge via the Internet at http://pubs.acs.org

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Notes

The authors declare no competing financial interest.

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