Research Article

A new methodology for quantifying on-site residential and commercial fossil fuel CO_2 emissions at the building spatial scale and hourly time scale



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In order to advance the scientific understanding of carbon exchange with the land surface, and contribute to quantitative-based US climate change policy interests, quantification of fossil fuel CO_2 emissions (the primary greenhouse gas), at fine spatial and temporal scales, is essential. Known as the 'Hestia Project', this pilot study has quantified 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 the greater Indianapolis region, IN, USA. Here, we describe the method used to quantify the on-site fossil fuel CO_2 emissions in the residential and commercial sectors. By downscaling the Vulcan Project's 2002 county-level commercial and residential fossil fuel CO_2 emissions, we quantified the CO_2 emissions for all building structures using a combination of multiple datasets and energy simulation. At the landscape scale, the spatial variation in CO_2 emissions is driven by building density, height and type. Within the urban core, larger emissions are driven by the larger amounts of energy consumed per unit floor area. The resulting dataset and corresponding methods will be of immediate use to city environmental managers and regional planning agencies, enabling the analysis of alternative strategies to lower fossil fuel CO_2 emissions. The results obtained here will also be a useful comparison to atmospheric CO_2 monitoring efforts aimed at constraining the land surface net carbon exchange via atmospheric sampling.

CO_2 emissions from fossil fuel combustion are the largest net annual flux of carbon in the earth–atmosphere system and represent the dominant source of greenhouse gas forcing [1]. In order to better understand other components of carbon exchange between the land, oceans and atmosphere, improved quantification of fossil fuel CO_2 fluxes are needed, because the fossil fuel CO_2 emissions component is often used as a boundary condition with low uncertainty when solving total carbon budgets [2]. Furthermore, US domestic climate change legislation is currently under consideration and requires both improved quantification of fluxes in order to establish emission baselines and identify of efficient and economically viable mitigation options. Both of these needs place importance on the quantification of fossil fuel CO_2 fluxes at finer space and time scales than have been achieved in the past [3].

At the global scale, fossil fuel CO_2 emissions had been resolved at the 1 × 1° spatial scale and, most commonly, on an annual time scale [4,5,101]. These inventories were constructed by distributing fossil fuel CO_2 emissions to the 1° grid using population density as a spatial proxy. These population-based inventories are useful in global studies but there are significant limitations to their use, since both scientific research and policy needs have begun to focus on regional understanding [6]. For example, at the county or state scale, population density is a poor predictor of large point sources, such as power plants, which are often not co-located with population centers [7]. Furthermore, the population-based inventories are not disaggregated by the economic sector, which is often a useful identifier in policy-making efforts and atmospheric monitoring, where multiple species such as carbon monoxide, ^{13}C and ^{14}C are used to identify emission sources [8–10].

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Key term

Energy consumption: Energy consumed in the form of fossil fuels by all consumption activities in an economy.

In the USA, the 'Vulcan Project' has attempted to overcome this limitation by generating fossil fuel CO_2 emissions estimations down to the subcounty spatial scale and the hourly time scale [11]. In addition to finer spatial and temporal scale estimation, the Vulcan Project quantifies emissions by fuel, economic sector and source classification. Although placed on a common 10 × 10 km grid, the underlying emissions data are characterized at a mixture of county, road and point source spatial scales [102]. Currently available for the year 2002, research is underway to quantify emissions for all years from 1990 to 2008, and ultimately achieve emissions delayed from real time by approximately 6 months.

These atmospheric/inventory measurement and model needs are driven, in part, by monitoring, reporting and verification (MRV) requirements that are emerging at local, national and international levels [12,13]. Similarly important are information needs to plan and optimize fossil fuel CO_2 mitigation strategies. For example, should an emissions-mitigation policy such as a cap-and-trade system become law, initial allocations and mitigation targets will be established (e.g., 17% reduction below 2005 levels by 2020) [14]. 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 are the greatest [15].

Energy consumption in urban environments is a major contributor to total fossil fuel CO_2 emissions [16,17]. For example, previous studies indicate that 37–86% of direct fuel consumption in buildings and industry and 37–77% of on-road gasoline and diesel consumption in the USA occurs in urban areas, depending on how the boundaries of the urban environment are defined [15]. Furthermore, 81% of the population of the USA lived in cities and suburbs in 2007 [18].

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 few studies have quantified fossil fuel CO_2 emissions at the scale of an entire county or city [16,17,19–21]. Other studies have attempted somewhat smaller spatial scales by quantifying emissions at the census tract or 'community' level [22,23]. As yet, no peer-reviewed research has attempted comprehensive quantification of fossil fuel CO_2 emissions at the scale of individual buildings or neighborhoods for the entirety of an urban landscape.

Similarly, the Vulcan Project has one important limitation in attempting to meet the needs of emission quantification at the urban landscape scale: 'area' sources, dominated by the residential and commercial sector, are only resolved at the scale of US counties. Given the importance of buildings as both sources of fossil fuel CO_2 emissions and as opportunities to mitigate emissions through improvements in building systems, such as insulation and space conditioning efficiency, quantifying Vulcan fossil fuel CO_2 emissions down to the individual building scale will accomplish a critical component of a complete urban landscape-scale fossil fuel CO_2 emissions data product.

In this study, we performed a spatial and temporal allocation of the county-level residential and commercial on-site fossil fuel CO_2 emissions from the Vulcan Project to the building/hourly space and time scales for the metropolitan Indianapolis, IN region. This study aims to establish an approach to quantify building-scale on-site fossil fuel CO_2 emissions across an entire urban landscape that can be reproduced across the USA, while maintaining quantitative linkages to the larger scale Vulcan inventory and, hence, the national-level greenhouse gas-accounting system. The method and results we describe here reflect the on-site fossil fuel consumption in these sectors. CO_2 emissions associated with electricity consumption in buildings are quantified at power plant locations and, hence, not included in the quantification described here. We use a combination of a building thermodynamic model and scaling arguments to quantify on-site emissions for all buildings in the metro Indianapolis region. Subsequently, we we describe the study area and the methods by which we downscaled the county-level residential and commercial on-site fossil fuel CO_2 emissions to the building/hourly space and time scales. We then provide results and discuss the drivers and the space and time patterns resulting from the allocation approach.

Methods

▪ Study area

Indianapolis/Marion County, IN, was chosen as the study area. Indianapolis is the county seat of Marion County, which has boundaries nearly identical to those of the city of Indianapolis. As most of the data are available at the county level, we performed all of the analysis for the Marion County domain, although the results are valid for either the county or city given their close spatial correspondence. The City of Indianapolis lies on the White River at its confluence with Fall Creek, near the centre of the state. The climate is typical of the east-central Midwest, with warm-to-hot summers and cold winters [103]. Climatological means for Indianapolis based on data from 1971–2000 indicate that the average annual temperature is 11.4°C with a summer average temperature of 23°C and a winter average temperature of -1°C. The total annual heating degree day value is 5521, and the cooling degree day value is 1042 [104]. It presently extends into nine Marion County Townships, including Pike, Washington, Lawrence, Wayne, Center, Warren, Decatur, Perry and Franklin. The city is located on a flat plain and is relatively symmetrical, having possibilities of expansion in all directions [24]. 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 the capital of the state of Indiana, Indianapolis was listed as the 14th largest city in the USA in 2008, with a population of 798,382 [105].

Method overview

The key elements of the methodology used to construct the building-level on-site fossil fuel CO_2 emissions employed in this study are shown in Figure 1. We focus on fossil fuel CO_2 emissions associated with on-site fuel combustion in the residential and commercial building sector. Energy use associated with electricity consumption at the building level is emitted at the power plant location. Since our focus is primarily aimed at understanding the carbon cycle at fine spatial and temporal scales, emissions are located at the point of energy combustion rather than energy demand. Emissions associated with electricity production, transportation and industrial activities are either described in previous literature on the Vulcan project [11] or in forthcoming papers.

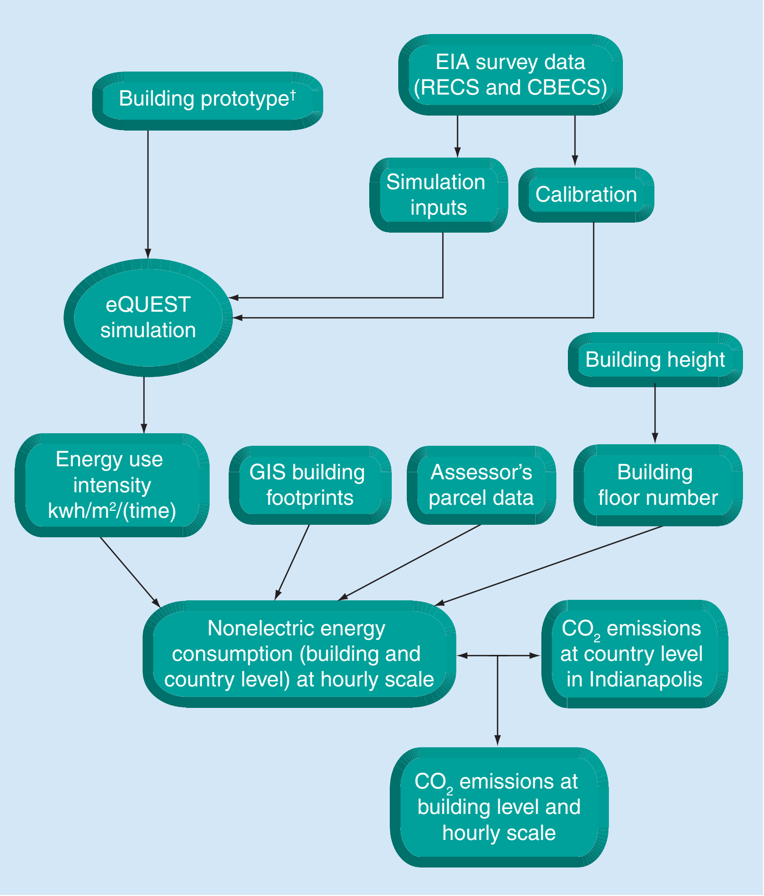

Figure 1. Methodology used to develop the building/hourly CO_2 emissions.
CBECS: Commercial building energy consumption survey; EIA: Energy information administration; GIS: Geographic information system; RECS: Residential energy consumption survey; eQUEST: Quick energy simulation tool.
†Data from [29–32].

County-level fossil fuel CO_2 emissions

The Marion County and Indiana state 2002 sectoral fossil fuel CO_2 emissions and percentage share, retrieved from the Vulcan Project, are shown in Table 1 [11]. The on-site residential and commercial CO_2 emissions, representing 21% of the total Marion County fossil fuel CO_2 emissions, are derived from 'area' sources, which represent diffuse emissions within an individual county in the USA. Although accounting for a little over 5% of the state-wide total fossil fuel CO_2 emissions, Marion County on-site residential and commercial emissions account for 13.9 and 12.3% of statewide emissions in the residential and commercial sectors, respectively. This is primarily due to the fact that Marion County has a lower percentage of both industrial and electricity production fossil fuel CO_2 emissions relative to the state as a whole.

Table 1. Sector-specific fossil fuel CO_2 emissions and percentage share for Marion county and Indiana in 2002.

	Emissions†						
	Commercial	Residential	Industrial	Electricity production	On-road	Aircraft	Nonroad
Marion County (MtC)	0.34	0.36	0.45	1.03	1.07	0.16	0.002
Percentage (%)	10	11	13	30	31	5	0
Indiana State (MtC)	2.76	2.59	12.63	32.18	10.29	0.88	1.36
Percentage (%)	4	4	21	51	16	1	2

†Emissions reflect on-site fuel combustion.
MtC: Million tonnes of carbon.

The Vulcan Project estimated residential and commercial area emission sources by utilizing CO emissions reported to the Environmental Protection Agency (EPA), typically estimated by state environmental agencies at the county and annual level with identification of the fuel and source classification code (SCC). The reported CO emissions are estimated via a wide variety of methods, outlined in EPA guidance documents [25–27]. For Marion County, the residential fossil fuel CO emissions are calculated on a fuel-by-fuel basis by apportioning the state residential fuel consumption to each county by the ratio of county households to total state households using that fuel [106,107]. This is then multiplied by a standard fuel-specific CO emission factor appropriate for residential consumption [108]. The commercial sector emissions apportion the statewide fuel-specific consumption to an individual county by the ratio of commercial sector employees in the county to the whole state [28,107].

In order to generate CO_2 emissions, the CO emissions are converted into fuel consumed via the CO emission factors reported by state or county officials. In the case of Marion County, this goes directly back to the county fuel consumption estimate. With estimates of standard fuel carbon content and oxidation fractions (assuming a gross calorific value or high heating value), CO_2 emissions are estimated. Only emissions associated with fuel combustion are included in the Vulcan estimates. For Marion county, a preliminary uncertainty has been estimated for the Vulcan residential and commercial sectors and encompasses the use of CO emission factors, heat content and carbon coefficients. For the commercial sector, we estimate the county-level commercial and residential uncertainties to be -11.7/+9.4% and -10.4/11.22%, respectively. A complete gridded uncertainty analysis for the Vulcan inventory is currently in preparation. A complete detailed description of the Vulcan Project methods can be found in Gurney *et al.* [11] and in the Vulcan online documentation [102].

Building typology & energy consumption simulation

A building typology was developed to describe the building types for the commercial and residential building stock in Indianapolis [29–32]. A total of 22 commercial and eight residential building categories were defined through examination of the building types in the Marion County Assessor's parcel database (Figure 2) [33]. The office and retail building categories were subdivided by size and age. A floor area of 25,000 ft^2 was used to subdivide these building categories into 'small' and 'large' subcategories [32]. Building vintage has an impact on energy consumption because of several factors such as insulation levels and heating, ventilatilation and air conditioning (HVAC) system efficiency [29]. Based on past research on energy consumption in buildings, we divided all buildings into pre-1980 and post-1979 age categories, with age identification derived from the local Assessor parcel data [29,32]. After defining these building types, a simplified 'zone' model (four perimeter zones and one core) was used to represent the complexity of commercial buildings [29]. Residential buildings were zoned into 'bedroom', 'general living' and 'unconditioned garage' [32]. These zones represent distinct internal space within individual buildings.

Hourly building-level energy use intensity (EUI) – the energy used per unit floor area – was simulated using the Quick Energy Simulation Tool (eQUEST) for each building type (US Department of Energy) [32,109]. eQUEST is a comprehensive building energy simulation front-end program based on the Department of Energy (DOE) building model, DOE2 that contains a series of driving variables and parameters in order to estimate energy consumption. The tool provides default values for all of the variable/parameter space, but also allows users to supply local data, where superior information is available. The major parameters for the building types used in eQUEST were derived from Huang *et al.* for the North Central US census region [29]. They include building

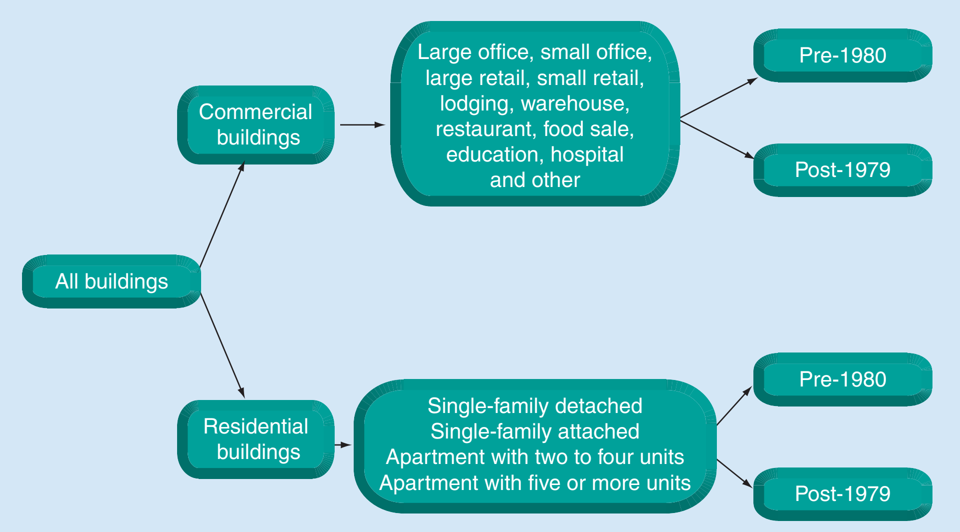

Figure 2. Typology of commercial and residential buildings used in this study.

shell characteristics (e.g., R value), internal load (e.g., lighting) and HVAC system characteristics. Indianapolis was specified as the location in the eQUEST simulation to retrieve the correct regional climate characteristics. Default values were used for the remaining parameters in the eQUEST system. For example, default values were used for the building schedules (occupancy), internal loads, HVAC schedules and domestic hot water use. We recognize that the use of default occupancy can introduce error compared with actual occupancy. However, we know of no comprehensive observational occupancy dataset for the buildings in Marion County.

The nonelectric EUI and EUI fuel ratio (the ratio of the nonelectric to electric EUI) values from the eQUEST simulation can be compared with the values derived from the DOE's energy information administration (EIA) residential energy consumption survey (RECS) and the commercial building energy consumption survey (CBECS) data for the East North Central Census Division [34,35]. In order to calibrate the eQUEST output to the regional average in each building category, the nonelectric EUI and EUI fuel ratio calculated using the eQUEST model was adjusted, following the Heiple and Sailor method, to match the surveyed values by adjusting the parameters for internal lighting and equipment power density [32]. After calibration, the simulated nonelectric EUIs were within 10% of the CBECS/RECS survey data, except for the restaurant and food sales building types, which were within 15% of the survey data **(Figure 3)**. The mean nonelectric EUI for all commercial and residential building types is 392 and 129 kWh/m^2, respectively (compared with 216 and 50 kWh/m^2 for electric EUI in commercial and residential building types, respectively). Within the commercial sector, the food sales building type has the largest nonelectric EUI, while large office buildings have the smallest. In the residential sector, apartments with two to four units have the largest nonelectric EUI, while single-family attached structures have the smallest. The spread of nonelectric EUI values among commercial buildings is larger than that among residential buildings.

The final energy consumption in each building was estimated from the calibrated nonelectric EUI from the eQUEST simulation, building area and number of floors (see equations below):

Equation 1

$$E^{fuel}_{building(i)} = EUI^{t} \times A_{building(i)} \times N_{building(i)}$$

where EUI^t is the nonelectric energy use intensity for building type t, $A_{building\,(i)}$ is the footprint area of building i, and $N_{building\,(i)}$ is the number of floors in building i.

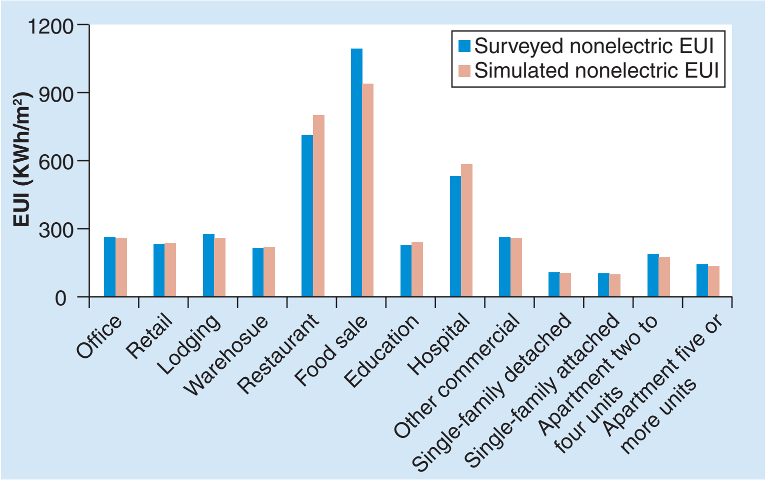

Figure 3. Comparison of simulated (after calibration) and surveyed nonelectric EUIs for commercial and residential buildings. The two age cohorts have been combined for all buildings.
EUI: Energy use intensity.

The floor area of each building was retrieved from a local geographic information system (GIS) database of building footprints [110]. A simple model was created to calculate the number of floors from building heights estimated from a remote sensing-based digital surface model and a digital elevation model [36]:

Equation 2

$$N_{building(i)} = \frac{H_{building(i)} - H1^{t}_{building}}{H1^{t}_{building}} + 1\left(if\ H_{building(i)} < H1^{t}_{building}\right)$$

$$N_{building(i)} = \frac{H_{building(i)} - H1^{t}_{building}}{HA^{t}_{building}} + 1\left(if\ H_{building(i)} > H1^{t}_{building}\right)$$

where $H_{building\,(i)}$ is the height of building i, $H1^{t}_{building}$ is the height of floor to ceiling for building type t, and $HA^{t}_{building}$ is the height of floor to floor for building type t.

Uncertainty analysis

Uncertainty associated with the building-level fossil fuel CO_2 emissions was analyzed using a Monte Carlo approach. The EUI can be used to represent the uncertainty manifest in the eQUEST simulation at the building level. In addition, the building height estimate, used to calculate the final building energy use, is also considered a source of uncertainty. The difference between the simulated and surveyed nonelectric EUI serves as the 2-σ uncertainty of a Gaussian nonelectric EUI probability density function. The digital surface model, which was used to derive building height, has a vertical accuracy of 1.8 m at the 95% confidence level [36]. A normal probability density function for each building height was constructed based on this 95% confidence level. The Monte Carlo approach was used to generate multiple outputs based on a random selection of these two uncertainty sources [37]. These outputs defined the final building-level energy consumption distribution from which a 95% uncertainty interval was retrieved.

Spatial & temporal allocation

The building-level residential and commercial energy consumption was used to spatially distribute the Vulcan Project's county-level fossil fuel CO_2 emissions for Marion County as shown in Equation 3:

Equation 3

$$C^{C}_{building(i)} = \frac{E^{fuel}_{building(i)}}{\sum_{i=1}^{n} E^{fuel}_{building(i)}} C^{C}_{county}$$

$$C^{R}_{building(i)} = \frac{E^{fuel}_{building(i)}}{\sum_{i=1}^{m} E^{fuel}_{building(i)}} C^{R}_{county}$$

where C^{C}_{County} and C^{R}_{County} are the commercial and residential fossil fuel CO_2 emissions at the county level, $C^{C}_{building\ (i)}$ and $C^{R}_{building\ (i)}$ are the commercial and residential building-level CO_2 emissions, n and m are the total number of commercial and residential buildings in the city, and $E^{Fuel}_{building\ (i)}$ is the fuel-based energy consumption in building i.

The county-level fossil fuel CO_2 emissions from the Vulcan Project are categorized by fuel type. Since we do not have information at the building level regarding what fuel is used in which structures, we assume a uniform spatial distribution of the fuel use. In reality, it is possible that there may be spatially coherent patterns of fuel type consumption.

Distribution of fossil fuel CO_2 emissions in time was performed by allocating the annual total according to the hourly fractional simulated building energy consumption, as shown in Equation 4:

Equation 4

$$C_{building(i,h)} = \frac{E^{fuel}_{building(i,h)}}{\sum_{h=1}^{8760} E^{fuel}_{building(i,h)}} C_{building(i,y)}$$

where $C_{building\ (i,h)}$ is the CO_2 emissions in hours (h) for building i, $C_{building\ (i,y)}$ is annual CO_2 emissions, and $E^{Fuel}_{building\ (i,h)}$ is the fuel-based energy consumption in hours (h) for building i.

Allocation from the county emissions estimate provides three advantages. First, the county-level estimate is tied to state and national-level fuel consumption statistics, which have a long history and consistent accounting methodology. The national fuel consumption statistics are constructed from domestic production and fuel-trade balances, which are considered to be very accurate (<5% error) at the total USA scale [38]. Second, the method is reproducible across the entire USA, given the comprehensiveness and methodological consistency of the Vulcan data product. Finally, the eQUEST building-level simulation provides energy demand only, with no guidance on fuel type. Given the sensitivity of final CO_2 emissions to fuel type (carbon content), an aggregate estimate constructed from the bottom-up is difficult. Although the estimate presented here is for a single year (2002), owing to the current estimation provided by the Vulcan inventory, a multiyear Vulcan inventory product is currently under development. Hence, the approach presented here could be applied to other years. However, trends at the subcounty scale would not be possible.

Results & discussion

Spatial pattern

The spatial distribution of annual CO_2 emissions at the building level, rescaled to 250-m spatial resolution and with a road overlay, is presented in Figure 4.

The spatial variation of fossil fuel CO_2 emissions is mainly caused by the building density, building height and building type. The largest commercial fossil fuel CO_2 emissions occur in the city center owing to greater building density and building height accompanied by large isolated emissions in the outer highway ring associated with commercial mall development. Similarly, there are large residential emissions associated with suburban development in the outer highway ring. Residential sector emissions are more homogeneous in space than in the commercial sector, with large emission values near the city center in older downtown neighborhoods and in progressively newer residential developments as one moves from the urban core to the new suburban developments in the outer ring.

The fossil fuel CO_2 emissions and uncertainty within each of the nine townships that comprise Indianapolis are shown in Figure 5. Within the commercial sector, the Center Township has the largest CO_2 emissions and the Decatur Township has the smallest. The largest commercial emissions in the Center Township are caused by a combination of larger nonelectric EUI and the larger building area and height. Within the residential sector, the Washington Township has the largest CO_2 emissions, and the Decatur Township has the smallest. The larger residential emissions in the Washington Township are driven primarily by the larger total residential building area, the variable with the greatest influence on overall township emissions. Although age is included in our model, the impact of the two age cohorts on the EUI is small compared with other variables.

▪ Monthly pattern

The hourly residential and commercial fossil fuel CO_2 emissions were aggregated to monthly totals for the nine townships and are presented in **Figure 6**. Both sectors exhibit strong seasonality, driven primarily by outside temperature with larger fossil fuel CO_2 emissions in winter and smaller emissions in summer months. The monthly patterns in the commercial sector exhibit four groupings defined primarily by the magnitude of the winter maximum. The Center Township, in a group by itself, has the largest winter peak emissions and somewhat elevated summer emissions compared with the other townships. Although the ratio of the winter to summer peaks is similar across the nine townships, the overall larger magnitude of annual emission in the Center Township gives rise to the larger midsummer value. In the residential sector, there is less clustering among the building types than that found in the commercial sector.

In order to evaluate the monthly pattern of the building-level fossil fuel CO_2 emissions, comparison is made to the EIA statewide natural gas consumption data [39]. **Figure 7** shows the monthly fraction of the annual total fossil fuel CO_2 emissions summed over all residential and commercial buildings as calculated in this study. The EIA data in **Figure 7** represents the monthly fraction of residential and commercial natural gas consumption for the state of Indiana. The two monthly patterns show similarities, although they reflect estimates driven by different data sources derived at different spatial domains. This suggests that the dominant determinants of residential and commercial fossil fuel CO_2 emissions (e.g., building types, climate and operation schedule) are similar across the county to state spatial domain in this US region. The similarity of the monthly pattern suggests that the methods developed here at the urban landscape scale are reasonable and consistent with the timing of state-level natural fuel consumption statistics.

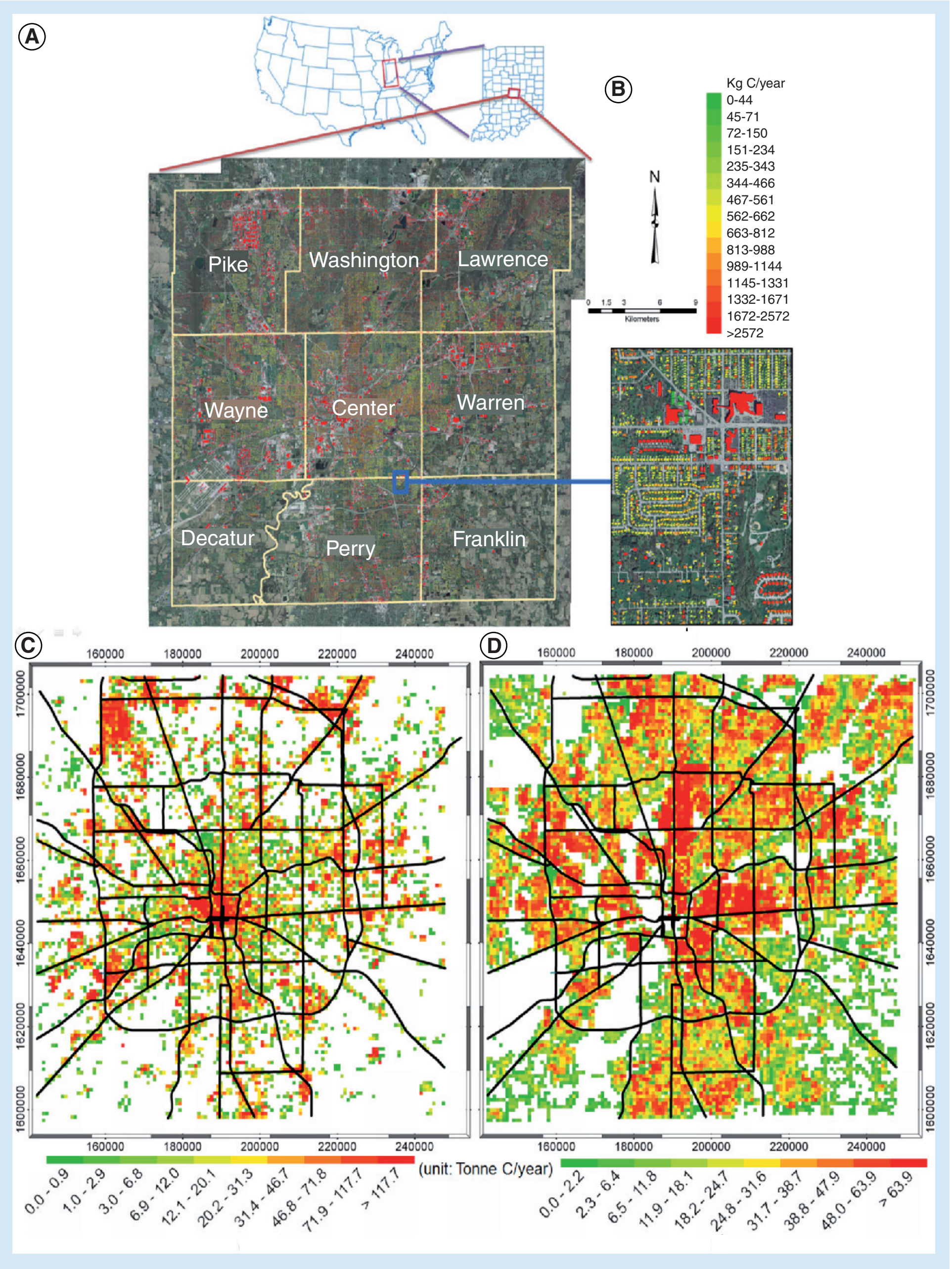

Figure 4. Building-level fossil fuel CO_2 emissions. (A) With township boundaries, **(B)** with an enlarged example neighborhood, **(C)** at 250-m spatial resolution for the commercial sector, and **(D)** for the residential sector.

▪ Diurnal pattern

Figure 8 shows the annual total diurnal pattern of fossil fuel CO_2 emissions for the sum of all residential and commercial buildings in the study domain. For the winter months (defined here as October–March) emissions

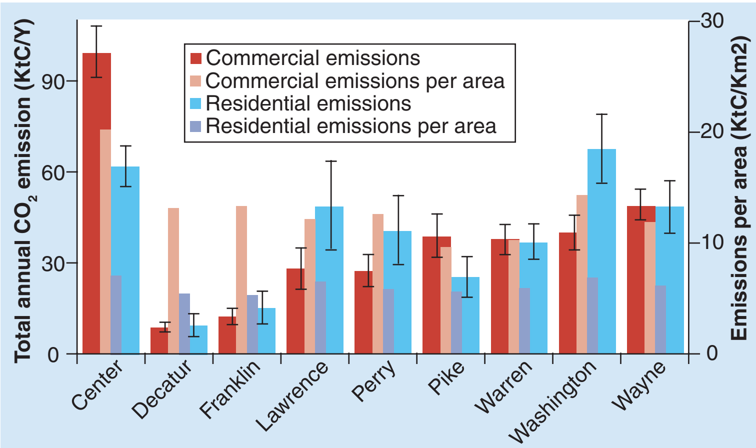

Figure 5. Total commercial and residential fossil fuel CO_2 emissions with 95% confidence interval for the nine townships within Marion County, Indianapolis, USA.

peak at approximately 9 am in the commercial sector, while the residential sector shows two peaks at approximately 6 am and 6 pm. Noteworthy is the fact that the morning residential emissions maximum precedes the commercial morning maximum by approximately 3 h and is within 20% of the commercial emissions magnitude. For the summer months (defined here as April–September), the magnitude of both commercial and residential emissions are much smaller than the winter months. The diurnal and seasonal emissions patterns are driven, in large measure, by the operating schedule of the commercial and residential building category convolved with external temperature.

▪ Emissions by building category

The annual total fossil fuel CO_2 emissions for each building category and uncertainties are summarized in **Figure 9**. Within the commercial sector, each building category contributes approximately 3–17% of total combined residential and commercial building emissions. Although the 'lodging', 'hospital', 'restaurant' and 'food sale' building categories have large emissions per unit area, their contribution to the total emissions at the county scale is relatively small compared with other building categories. This is due to the small total floor area of these building categories within the county as a whole. Within the residential sector, the 'single-family detached' building category has the largest total fossil fuel CO_2 emissions, which account for approximately 40% of the combined residential and commercial building emissions and 80% of the total emissions from the residential sector. This is primarily driven by the large share (82%) that single-family detached housing accounts for out of the total residential floor area. This result highlights the importance of the single-family detached building category when considering CO_2 emissions mitigation policies.

Conclusion

Quantification of fossil fuel CO_2 emissions at the urban landscape scale offers a key element to understanding the total carbon budget at scales commensurate with the advent of multi-tiered atmospheric monitoring systems. Process-driven quantification also offers opportunities to support greenhouse gas decision making at the scales that many decisions are made – the individual building and roadway scale. Of

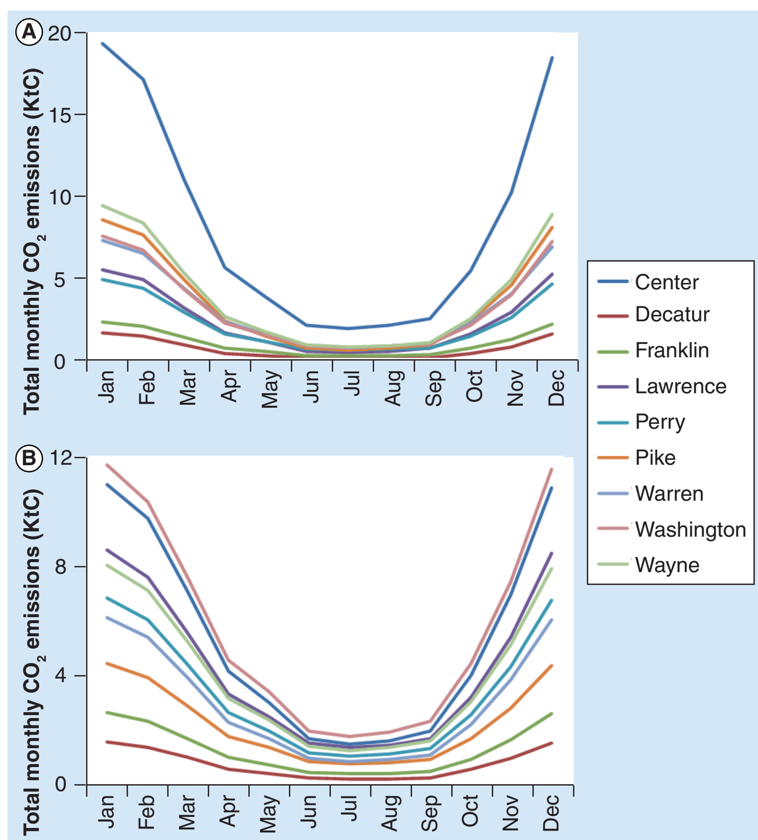

Figure 6. The monthly (A) commercial and (B) residential fossil fuel CO_2 emissions in the nine townships within Marion County, Indianapolis, USA.

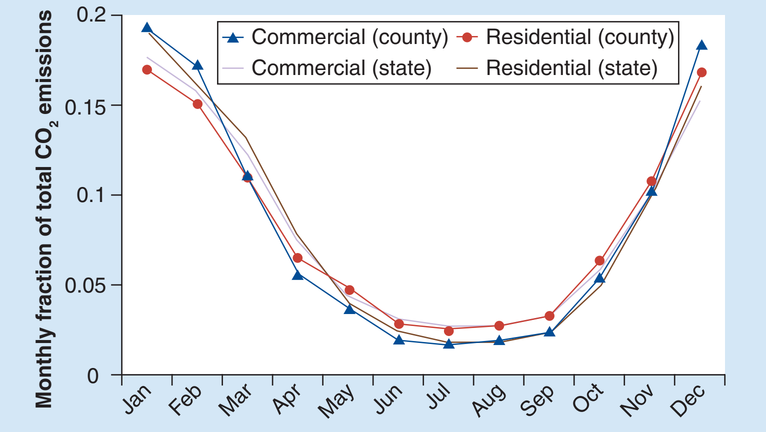

Figure 7. Comparison of the monthly fractions of residential and commercial department of energy/energy information administration state-total natural gas consumption to the on-site residential and commercial fossil fuel CO_2 emissions estimated in this study for Marion County, Indianapolis, USA.

the sources of fossil fuel CO_2 emissions, one of the most challenging has been the building sector, mostly comprised of commercial and residential structures.

In this study, we have attempted to quantify the 2002 residential and commercial on-site fossil fuel CO_2 measurements for all buildings, every hour for the city of Indianapolis. We have accomplished this by allocating the county-level Vulcan fossil fuel CO_2 inventory for the residential and commercial sectors into the buildings within the city through the use of a building thermodynamic model combined with regional DOE energy use efficiency survey data, Assessor's parcel data, GIS-derived floor area and remotely sensed building height data. This approach utilizes a process-driven method at the building level, while maintaining consistency with larger-scale fuel consumption statistics. We analyzed the spatial and temporal patterns of the building-level fossil fuel CO_2 emissions by building type, township, season and hour.

For the city of Indianapolis we find that the spatial variation across the urban landscape is driven by the density of buildings, their height and type. Fossil fuel CO_2 emissions from the commercial sector dominate in the urban center with residential emissions most prominent in the suburban pockets associated with the outer ring highway. The larger overall emissions in the urban central district are due primarily to the larger nonelectric energy use intensity and the larger average building size.

Although the total magnitude of the annual CO_2 emissions differ from one township to the next, the distribution of fossil fuel CO_2 emissions over time exhibit familiar monthly patterns, with winter maxima and a consistent peak-to-peak magnitude across the nine townships that comprise the total urban landscape.

The diurnal patterns show a delayed morning peak in the commercial versus residential sector with a weakened evening maximum compared with that found in the residential sector. Both sectors show morning peaks that are slightly earlier in the summer versus winter months.

The contribution to the total emissions is fairly evenly distributed across commercial building type categories, whereas the single-family detached house type contributes a large share of the residential emissions total due to both the higher energy-use intensity and the larger total floor area.

The approach developed here and the results for Indianapolis suggest that building scale CO_2 emissions for the entirety of an urban landscape are achievable and potentially reproducible in other urban areas. An excellent dataset that would complement the work performed here is utility billing data, at a sub-county aggregate scale and certainly at the building-by-building scale. However, such data is not ubiquitously available and, hence, can only be utilized in those locations where utility collaboration is possible.

The 10-k spatial resolution fossil fuel-based emission estimates from Vulcan project are beginning to be used to obtain the regional, biospheric carbon fluxes via transport model inversion approaches constrained by atmospheric measurements of CO_2. The higher temporal and spatially resolved urban-scale CO_2 inventories

Key term

Fossil fuel CO_2: Emissions to the atmosphere of carbon dioxide that are due to the combustion of fossil fuels (e.g., coal, oil or natural gas).

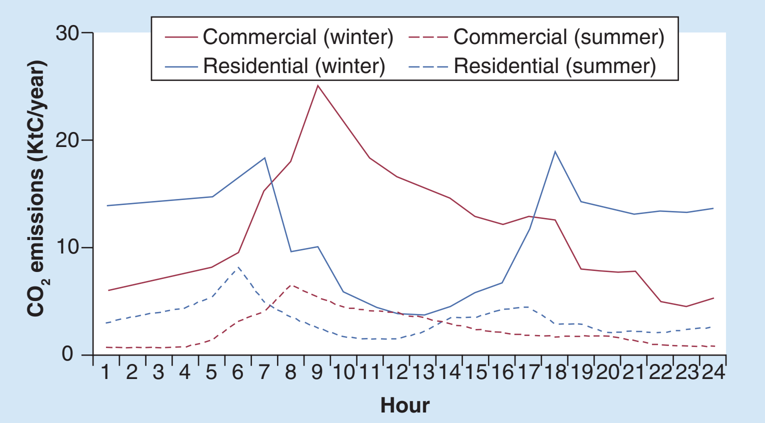

Figure 8. Diurnal pattern of summer and winter on-site fossil fuel CO_2 emissions in the residential and commercial sectors in Marion County, Indianapolis, USA.

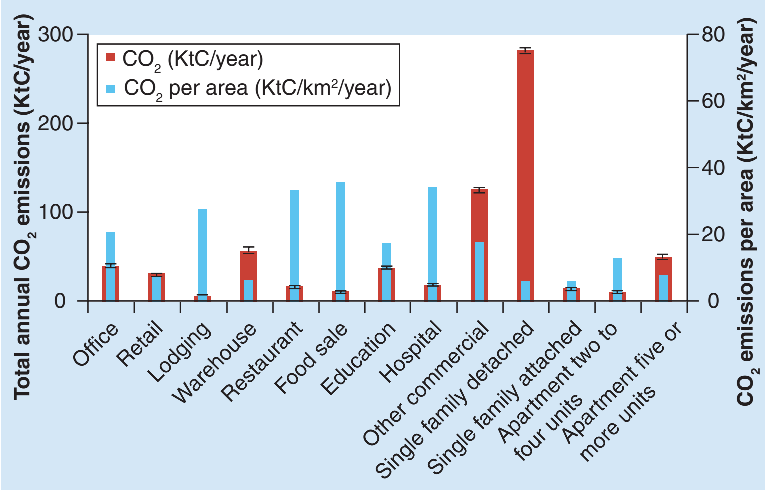

Figure 9. Annual total commercial and residential on-site fossil fuel CO_2 emissions (with 95% confidence interval) summed by building category and the emissions per unit area.

Key term

High resolution: Spatial resolution that is finer than the US county scale and temporal resolution that is hourly.

offer better information for a 'top-down'/'bottom-up' convergence of observations and models on the carbon cycle.

This high spatiotemporal urban CO_2 emissions data inventory can improve understanding of CO_2 emissions drivers, thereby assisting in baselining emissions, projecting future trend, and the development of cost-effective mitigation strategies that reflect the socioeconomic conditions unique to this metropolitan region. More importantly, this effort can serve as a methodological guide to a comprehensive **high resolution** inventory for all urbanized areas, ultimately moving fossil fuel CO_2 emissions quantification to the building level across the landscape of the USA.

Future perspective

Two research needs within carbon cycle science and carbon emissions mitigation have emerged in recent years and are converging on a common solution. Carbon cycle studies that attempt to close carbon budgets are attempting to improve the 'process' understanding of carbon exchange and this is best done at smaller space and time scales, where mechanisms can be observed and modeled. Mitigation efforts require knowledge of the drivers of emissions and these efforts are most effective when applied at the local scale, where most energy/emissions decisions are made. Hence, there is growing interest and progress aimed at the quantification of carbon emissions at the scale of buildings and streets. This trend will likely intensify as both policy needs and atmospheric measurements advance.

Financial & competing interests disclosure

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Executive summary

- We have quantified all fossil fuel CO_2 emissions down to the individual building for the city of Indianapolis, IN, USA.
- In this article we describe the method employed to quantify emissions for the building sector.
- At the landscape scale, the spatial variation in CO_2 emissions is driven by building, density, height and type.
- Within the urban core, larger emissions are driven by the larger amounts of energy consumed per unit floor area.
- The distribution of fossil fuel CO_2 emissions over time exhibit winter maxima and a consistent peak-to-peak magnitude across the nine townships.
- The diurnal patterns are a delayed morning peak in the commercial versus residential sector with a weakened evening maximum.
- The approach developed here and the results for Indianapolis suggest that building scale CO_2 emissions for the entirety of an urban landscape are achievable and potentially reproducible in other urban areas.
- This can contribute to CO_2 emissions mitigation efforts and to assisting with understanding regional and urban carbon budgets in cooperation with atmospheric measurements.

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