CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions in the residential and commercial sectors. By downscaling the Vulcan Project’s 2002 county-level commercial and residential fossil fuel CO₂ emissions, we quantified the CO₂ emissions for all building structures using a combination of multiple datasets and energy simulation. At the landscape scale, the spatial variation in CO₂ 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 CO₂ emissions. The results obtained here will also be a useful comparison to atmospheric CO₂ monitoring efforts aimed at constraining the land surface net carbon exchange via atmospheric sampling.

At the global scale, fossil fuel CO₂ 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 CO₂ 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, ¹³C and ¹⁴C are used to identify emission sources [8–10].
In the USA, the ‘Vulcan Project’ has attempted to overcome this 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 CO₂ emissions and as opportunities to mitigate emissions through improvements in building systems, such as insulation and space conditioning efficiency, quantifying Vulcan fossil fuel CO₂ emissions down to the individual building scale will accomplish a critical component of a complete urban landscape-scale fossil fuel CO₂ emissions data product.

In this study, we performed a spatial and temporal allocation of the county-level residential and commercial on-site fossil fuel CO₂ 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 CO₂ 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. CO₂ 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 describe the study area and the methods by which we downscaled the county-level residential and commercial on-site fossil fuel CO₂ 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.

- **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>
<thead>
<tr>
<th>Table 1. Sector-specific fossil fuel CO$_2$ emissions and percentage share for Marion county and Indiana in 2002.</th>
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<tbody>
<tr>
<td><strong>Emissions</strong></td>
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<tr>
<td>Marion County (MtC)</td>
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<tr>
<td>Percentage (%)</td>
</tr>
<tr>
<td>Indiana State (MtC)</td>
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<td>Percentage (%)</td>
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</tbody>
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*Emissions reflect off-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 CO₂ 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), CO₂ 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 ft² 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, ventilation 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...
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 retain 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 meet 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/m², respectively (compared with 216 and 50 kWh/m² 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):

\[ E_{\text{building}}^{\text{final}} = EU_{t} \times A_{\text{building}t} \times N_{\text{building}t} \]

where \( EU_{t} \) is the nonelectric energy use intensity for building type \( t \), \( A_{\text{building}t} \) is the footprint area of building \( i \), and \( N_{\text{building}t} \) 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.](image)

- **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 uncertainty of a Gaussian nonelectric EUI probability density function. The digital surface model, which was used to derive building height, has a vertical

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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:

$$ C_{\text{building}}^{C} = \frac{E_{\text{fuel}}^{\text{building}}(i)}{C_{\text{county}}^{C}} \sum_{i=1}^{n} E_{\text{building}}^{\text{fuel}}(i) $$

$$ C_{\text{building}}^{R} = \frac{E_{\text{fuel}}^{\text{building}}(i)}{C_{\text{county}}^{R}} \sum_{i=1}^{m} E_{\text{building}}^{\text{fuel}}(i) $$

where $C_{\text{county}}^{C}$ and $C_{\text{county}}^{R}$ are the commercial and residential fossil fuel CO$_2$ emissions at the county level, $C_{\text{building}}^{C}(i)$ and $C_{\text{building}}^{R}(i)$ 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 $E_{\text{fuel}}^{\text{building}}(i)$ 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:

$$ C_{\text{building}}(i,h) = \frac{E_{\text{fuel}}^{\text{building}}(i,h)}{C_{\text{building}}(i,h)} \sum_{h=1}^{H} E_{\text{building}}^{\text{fuel}}(i,h) $$

where $C_{\text{building}}(i,h)$ is the CO$_2$ emissions in hours ($h$) for building $i$, $C_{\text{building}}(i,h)$ is annual CO$_2$ emissions, and $E_{\text{fuel}}^{\text{building}}(i,h)$ 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 fossil fuel consumption statistics, which have a long history and consistent accounting methodology. The national fossil 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. 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
towship 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.

- **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
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
the sources of fossil fuel CO₂ 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 CO₂ measurements for all buildings, every hour for the city of Indianapolis. We have accomplished this by allocating the county-level Vulcan fossil fuel CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions differ from one township to the next, the distribution of fossil fuel CO₂ 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 CO₂ 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 CO₂. The higher temporal and spatially resolved urban-scale CO₂ inventories
and the emissions per unit area.

emissions (with 95% confidence interval) summed by building category
\[ f_i \]

Papers of special note have been highlighted as:

Bibliography

9. Annual total commercial and residential on-site fossil fuel CO₂ emissions.

Figure 9. Annual total commercial and residential on-site fossil fuel CO₂ 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.

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

This research was supported through a grant from the Purdue Showalter Trust and a gift from Knauf Insulation. The authors have a patent pending for this methodology. The authors have no other relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript apart from those disclosed. No writing assistance was utilized in the production of this manuscript.

Executive summary

- We have quantified all fossil fuel CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions for the entirety of an urban landscape are achievable and potentially reproducible in other urban areas.
- This can contribute to CO₂ emissions mitigation efforts and to assisting with understanding regional and urban carbon budgets in cooperation with atmospheric measurements.

Bibliography

Papers of special note have been highlighted as:

- of interest
- of considerable interest


Methodology for quantifying on-site residential & commercial fossil fuel CO₂ emissions


Provides description of the county-level CO₂ emissions constraint to this work.


Spatially explicit treatment of residential emissions.


Important methodological approach to estimate building-level energy consumption.


Websites


Vulcan Project (2008): high-resolution fossil fuel emission estimates in support of NACP CO₂ measurement and assimilation systems. www.purdue.edu/eas/carbon/vulcan


