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RESEARCH ARTICLE

Reconciling the differences between a bottom-up and inverse-estimated $FFCO_2$ emissions estimate in a large US urban area

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The INFLUX experiment has taken multiple approaches to estimate the carbon dioxide (CO_2) flux in a domain centered on the city of Indianapolis, Indiana. One approach, Hestia, uses a bottom-up technique relying on a mixture of activity data, fuel statistics, direct flux measurement and modeling algorithms. A second uses a Bayesian atmospheric inverse approach constrained by atmospheric CO_2 measurements and the Hestia emissions estimate as a prior CO_2 flux. The difference in the central estimate of the two approaches comes to 0.94 MtC (an 18.7% difference) over the eight-month period between September 1, 2012 and April 30, 2013, a statistically significant difference at the 2-sigma level. Here we explore possible explanations for this apparent discrepancy in an attempt to reconcile the flux estimates. We focus on two broad categories: 1) biases in the largest of bottom-up flux contributions and 2) missing CO_2 sources. Though there is some evidence for small biases in the Hestia fossil fuel carbon dioxide ($FFCO_2$) flux estimate as an explanation for the calculated difference, we find more support for missing CO_2 fluxes, with biological respiration the largest of these. Incorporation of these differences bring the Hestia bottom-up and the INFLUX inversion flux estimates into statistical agreement and are additionally consistent with wintertime measurements of atmospheric $^{14}CO_2$. We conclude that comparison of bottom-up and top-down approaches must consider all flux contributions and highlight the important contribution to urban carbon budgets of animal and biotic respiration. Incorporation of missing CO_2 fluxes reconciles the bottom-up and inverse-based approach in the INFLUX domain.

Keywords: carbon footprint; carbon flux; fossil fuel CO_2

1. Introduction

Anthropogenic carbon dioxide (CO_2) emission, primarily from the combustion of fossil fuels, is the largest net annual flux of CO_2 to the atmosphere and represents the dominant source of greenhouse gas forcing (*Hansen et al.*, 1998; *LeQuere et al.*, 2013). Anthropogenic 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 (*Gurney et al.*, 2007; *Heimann et al.*, 2008). Similarly, 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 to establish emission baselines, substantiate emission trajectories, and for the identification of efficient, economically-viable greenhouse gas mitigation options (e.g. *Kennedy et al.*, 2010).

All of the motivations for understanding and quantifying fluxes of CO_2 are equally applicable to the urban domain, where recent years have seen increasing interest and importance. This interest is driven, in no small part, by the recognition that urban areas currently account for over 70% of energy-related CO_2 emissions and are projected to triple in extent between 2000 and 2030 (*Seto* 2012; *IEA*, 2008).

Just as with the larger scales, improved understanding of the carbon flows in cities offers several practical outcomes for urban stakeholders. Quantification of the impacts of mitigation efforts or programs and their effective management remains an important need as more cities agree to voluntary or legislated reduction targets. Similarly

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important are information needs to plan and optimize mitigation strategies. 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 (*Rosenzweig et al.*, 2010; *Fleming and Webber*, 2004; *Salon et al.*, 2010; *Betsill and Bulkeley*, 2006; *Dhakal and Shrestha*, 2010).

The Indianapolis Flux Experiment (INFLUX) experiment emerged from research aimed at quantifying space- and time-explicit fossil fuel carbon dioxide emissions (Hestia) in the city of Indianapolis (*Gurney et al.*, 2012; *Davis et al.*, 2017). The INFLUX effort now includes the original bottom-up quantification system, aircraft-based in situ measurement of CO_2, CH_4, and CO fluxes, and dense, tower-based continuous measurement of mole fraction for CO_2, CH_4, and CO (*Cambaliza et al.*, 2014, 2015; *Heimburger et al.*, 2017; *Miles et al.*, 2016) and flask measurements of CO_2, CH_4, CO, $^{14}CO_2$ and a host of other species (*Turnbull et al.*, 2012; *Turnbull et al.*, 2015). INFLUX has also seen the application of an inverse modeling system that integrates both the bottom-up information, atmospheric observations and atmospheric transport simulation to arrive at an optimal estimate of the total CO_2 flux in an area centered on the City of Indianapolis (*Lauvaux et al.*, 2016). This last research step – the integration of the bottom-up flux estimation with the atmospheric mole fraction measurements and simulated transport – is important in that it paves the way for an information system that integrates multiple approaches to quantifying urban carbon fluxes. Furthermore, these different approaches have complementary strengths – bottom-up estimation is rich with mechanistic and space/time detail but suffers from potential biases in the data and model assumptions used. Atmospheric approaches, by contrast, reliably capture the entire flux but face difficulties in capturing flux detail and remain sensitive to assumptions about atmospheric transport and boundary conditions.

Notable among the recent analysis integrating these two approaches to urban flux estimation, was the difference between the Hestia bottom-up $FFCO_2$ flux estimation of Gurney et al. (2012) and the atmospheric CO_2 inversion result of Lauvaux et al. (2016) in the INFLUX effort. Though the lowest value of the complete atmospheric inversion ensemble range overlapped the upper 2-sigma boundary of the Hestia $FFCO_2$ flux probability distribution, the reference atmospheric inversion and its posterior uncertainty, however, did not. Importantly, the central estimate of the reference inversion was greater than the bottom-up flux estimate by approximately 20% (0.94 MtC) over the eight-month period from September 2012 to April 2013.

Here we consider a simple question regarding the differing estimates of $FFCO_2$ emissions in the INFLUX domain: Can the bottom-up estimation method account for the 0.94 MtC difference between the Hestia $FFCO_2$ flux estimate and that inferred through the atmospheric CO_2 inversion. We consider numerous potential sources of bias in the Hestia estimation approach to identify the most likely candidates for the difference. This includes examination of an updated version (version 3.0) of the Hestia $FFCO_2$ emissions which made significant changes to the onroad and nonroad emitting sectors. We also consider the possibility of "missing" flux sources – emissions that may be reflected in the mixing ratio measurements but not explicitly included in the prior flux.

We describe our methods in section 2.0 which is mostly a description of the updates to the Hestia Indianapolis $FFCO_2$ emissions data product. In section 3.0, we present the results of our exploration of possible explanations for the difference between the Lauvaux et al. (2016) atmospheric inversion flux estimate and the bottom-up Hestia $FFCO_2$ emissions estimate. In section 4.0 we discuss the most likely candidates that may account for the differences, note the complementary results from the $^{14}CO_2$ monitoring, and discuss methods by which future work can more fully account for biases and missing fluxes, offering some near-term research objectives for further work in the INFLUX effort.

2. Methods

2.1 Hestia-Indianapolis Version 3.0

A new estimate of $FFCO_2$ emissions for Marion County, IN (the location of Indianapolis City) has been generated from the Hestia Project (Hestia-Indianapolis Version 3.0). The previous version (version 2.0) generated a $FFCO_2$ emissions estimate for Marion County and the eight counties surrounding Marion County, but using simpler techniques. The Hestia version 2.0 $FFCO_2$ flux estimate was anchored to the year 2002 and made scaled estimates in all economic sectors (e.g. residential, commercial, industrial, etc.), other than electricity production, for the years 2010–2013 (*Gurney et al.*, 2012). The scaled estimates used statewide fuel sales/consumption statistics from the Department of Energy's Energy Information Agency (DOE EIA). For the larger power plants in the electricity production sector, direct stack monitoring of $FFCO_2$ fluxes were available for all years. For a complete description of the methods employed in the Marion County Hestia version 2.0 $FFCO_2$ flux estimate, see Gurney et al., 2012.

The new version (version 3.0) includes a series of improvements over the version 2.0 estimate. The most important update is the use of the Environmental Protection Agency National Emissions Inventory (NEI) results for the year 2011. This data is relevant to the $FFCO_2$ estimates made for all sectors other than electricity production. Version 3.0 extends the time series to the year 2014 using the same DOE EIA scaling described previously but using the year 2011 as the base year. This offers the opportunity to compare the scaling of version 2.0 to the reported data in version 3.0 for the common year of 2011. Additional improvements were made to the spatial distribution of emitting sources. For example, the onroad sector used an improved road basemap and improved Annual Average Daily Traffic (AADT) data, both of which are used to distribute the county-level estimates of onroad $FFCO_2$ emissions to individual road segments. The improved road basemap had a larger number of individual road classes and a better match to the NEI onroad county-level estimates of $FFCO_2$. The onroad NEI results were driven by the MOVES model as opposed to the NMIM modeling system used in the version 2.0 estimate. MOVES is considered a superior model system for characterizing onroad emissions (*Vallamsundar and Lin*, 2011; *Fujita et al.*, 2012). In version 2.0 the nonroad emissions sector contained no spatial distribution but was evenly spread across Marion County. Version 3.0 employs a series of spatial surrogates derived from EPA data (US EPA; ftp.epa.gov/EmisInventory/surrogates/surrogates_2010). Finally, the point source distribution was improved with more accurate geolocation of point sources, a critical element in linkage to atmospheric modeling.

3. Results

3.1 Hestia version 2.0 and Lauvaux et al. flux inversion

Lauvaux et al. (2016) performed an atmospheric CO_2 inversion for a domain that was centered on the city of Indianapolis (within Marion County) but included the eight counties that surround Indianapolis: Johnson, Morgan, Madison, Hendricks, Shelby, Boone, and Hancock. The inversion generated posterior flux estimates using a five-day moving window between September 2012 and April 2013. The reference case inversion arrived at a posterior flux estimate of 5.5 MtC (one-sigma = ±0.20 MtC). Because the regional atmospheric CO_2 inversion includes assumptions regarding key components of the inversion problem not reflected in either the prior flux or atmospheric measurement uncertainties, the study included a number of sensitivity cases. This resulted in a wider range of posterior flux outcomes which were represented as a numerical span, rather than a probability distribution. The sensitivity cases included variation in the assumed prior error correlation lengths and variation in the time window of observed CO_2 mixing ratios used. The complete ensemble posterior flux for the entire domain ranged from 4.53 MtC to 6.51 MtC.

The Hestia version 2.0 $FFCO_2$ emissions were used as the prior flux in both the Lauvaux et al. (2016) reference case inversion and all the sensitivity cases but one (the case testing the influence of a different prior flux). The Hestia $FFCO_2$ prior flux for the September 2012 to April 2013 period, came to 4.56 MtC/yr, or an 18.7% (0.94 MtC) difference from the inversion reference case posterior flux. Integration of the Hestia version 2.0 $FFCO_2$ flux in its native format over the September to April period, arrives at a total flux of 4.6 MtC/year, slightly higher than the prior used in the inversion experiment (0.04 MtC: 0.9%). The difference is likely due to small inaccuracies commonly encountered in the regridding routines applied to the Hestia values.

Quantification of uncertainty for the Hestia $FFCO_2$ flux data product is particularly difficult since the flux estimation relies to a great extent on self-reported or regulatory-based data sources which are rarely accompanied by uncertainty. Hence, it remains an ongoing effort within the Hestia research to quantify uncertainty and this will be reported with future releases of the Hestia data product. However, in order to supply the atmospheric CO_2 inversion with a required prior flux error, the flux variance assumed at the pixel scale (model grid box) was 60% of the total prior flux in a given pixel based on expert judgement. To arrive at a total domain prior flux uncertainty, a error correlation length of 4km was combined with an urban mask (correlation only occurs between emitting pixels). This resulted in a one-sigma posterior uncertainty for the whole domain of 0.23 MtC. This means that the lower bound of the 2-sigma reference case inversion result (5.10 MtC) does not overlap with the upper bound of the 2-sigma Hestia $FFCO_2$ prior flux value (5.01 MtC).

The Marion County portion of the prior and posterior flux was 2.86 and 3.74 MtC/yr, respectively (a difference of 0.88 MtC/yr), representing a 26% increase between the Hestia $FFCO_2$ prior flux and the posterior flux. The majority of the flux correction (94%) made by the inversion analysis were located within Marion County as opposed to the eight surrounding counties (**Figure 1**). This is not surprising given that the atmospheric monitoring locations were more sensitive to fluxes in Marion County and the magnitude of the fluxes in Marion County were considerably larger than any of the surrounding counties. As the center of commerce in this region and hosting 54% of the population, this result is consistent with expectation. The spatial distribution of the flux correction (*Lauvaux et al.*, 2016, Figures 13 and 15) further confirms this pattern with the dominant flux correction corresponding to the road network and the greater density of residential and commercial buildings in the urban core.

3.2 Difference Hypotheses

As mentioned, the Hestia $FFCO_2$ emissions data product was used as the prior flux within the INFLUX inversion, a necessary constraint given the limitations of the atmospheric CO_2 observational constraint and the uncertainties intrinsic to the atmospheric transport simulation. The role of the prior flux is to offer a reasonable and physically consistent initial flux distribution that the combination of atmospheric observations and atmospheric transport adjust, as needed in the optimization process. One can also consider the inverse result as an important and independent constraint to the generation of a flux data product using the bottom-up technique. In this way, one might examine what potential adjustment to the bottom-up flux construction would be consistent with the inversion result and the internal constraints in the bottom-up data and algorithms. Similarly, there are elements of the measured atmospheric CO_2 that are not intentionally captured in the Hestia $FFCO_2$ emissions data product and these may be explored as an alternative explanation for the 0.94 MtC/yr discrepancy between the two approaches to the flux estimation.

3.2.1 Hestia $FFCO_2$ sectoral error sources

The Hestia $FFCO_2$ emissions for Marion County and the eight counties surrounding Marion County for the eight-month period from September 2012 to April 2013, are dominated by the onroad emission sector (2.24 MtC/yr; 48.2%) followed by the electricity production sector (0.95 MtC/yr; 20.5%), the residential and commer-

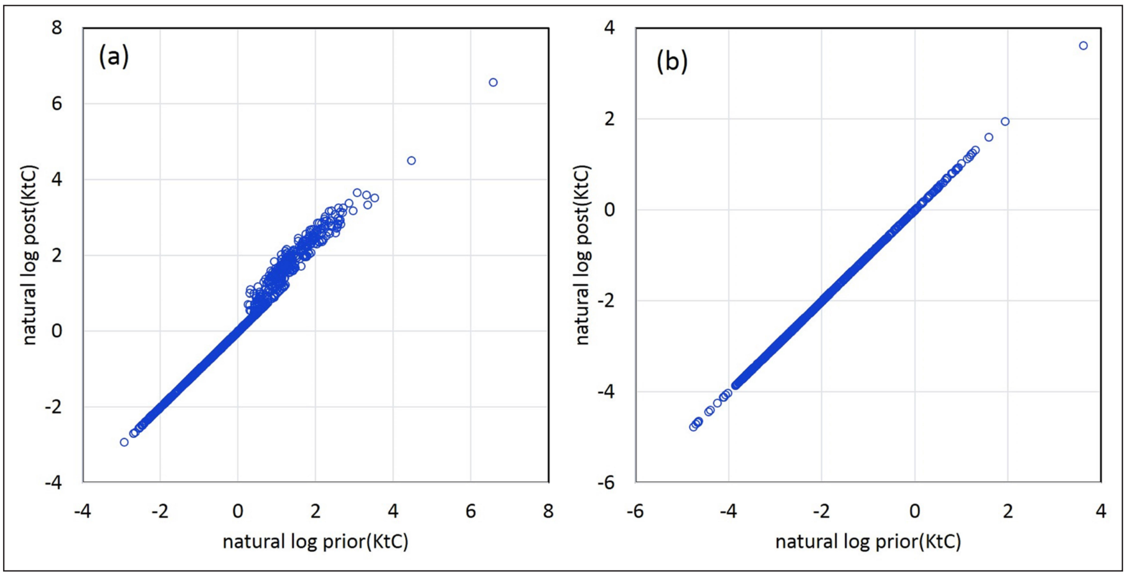

Figure 1: Prior versus posterior gridded CO_2 emissions. Scatterplot of the Lauvaux et al. (2016) inversion reference case prior versus posterior CO_2 emissions at the scale of 1 kilometer × 1 kilometer gridcells in units of natural log kiloton carbon for **a)** Marion County, Indiana; **b)** eight surrounding counties. DOI: https://doi.org/10.1525/elementa.137.f1

cial buildings (0.62 MtC/yr; 13.4%), the industrial sector (0.45 MtC/yr; 9.7%), and nonroad/rail/airport sectors (0.39 MtC/yr; 9.3%). Here, we consider the three largest of these sectoral divisions, in turn, as candidates for flux bias in the Hestia $FFCO_2$ emissions.

Onroad: As the largest single emitting sector in the domain, onroad $FFCO_2$ emissions bear closer examination as these could be considered a likely candidate for underestimation in the domain-wide Hestia $FFCO_2$ emissions estimate. The approach taken in the Hestia project is to use output of the MOVES 2010b model. It takes county total estimates of vehicle miles traveled (VMT) within each of the nine counties and combines this information with estimates of the onroad fleet of vehicles, their age distribution and fuel economy (*USEPA* 2015) to estimate $FFCO_2$ emissions for each county. County totals for 14 road and six vehicle classes are distributed to the roads based on the road segment-level VMT which is the product of measured average annual daily traffic (AADT) counts and road segment lengths.

Additional estimates of onroad $FFCO_2$ emissions in the INFLUX domain from September 2012 to April 2013 – 2.24 MtC – can be approached using methods independent the Hestia approach. We use the DOE EIA survey-based estimates of 2012 and 2013 "sales/deliveries to onroad consumers" of both diesel and gasoline in the state of Indiana (see **Table 1**) (*USDOE* 2016). We convert these sales/deliveries to carbon using standard heat and carbon content values for No 2 diesel and gasoline (10.07 tCO_2/e3gals, 9.12 tCO_2/e3gals). We average the two years and extract 8/12 of the total, to capture an equivalent eight months of flux straddling the two years, 2012 and 2013. Finally, we take the statewide proportion of this value according to the US Census 2012/2013 total population of the nine counties in the INFLUX domain, arriving at 1.99 MtC (*US Census*, 2016b).

Because commercial onroad emissions (delivery trucks, interstate commerce, etc.) may be underestimated by a distribution based on the share of statewide population in the nine counties, we also examine the county share of statewide total retail sales in the nine counties (*US Census*, 2016a). Hence, the state total onroad diesel and gasoline are apportioned to the nine counties based on their share of retail sales. The use of retail sales results in an onroad $FFCO_2$ emissions estimate of 2.25 MtC, a value nearly identical to the Hestia onroad $FFCO_2$ emissions estimate of 2.24 MtC.

Finally, we use a recently published high-resolution onroad $FFCO_2$ emissions data product, DARTE, generated for the United States (*Gately et al.*, 2015). This estimate, though also a bottom-up technique, used a somewhat different approach to onroad emissions, opting to calculate emissions directly from annual average daily traffic (AADT) estimates and statewide proportions of different vehicle classes and their associated travel efficiency. The last year of the DARTE data product is 2012 and has no sub-annual temporal structure. Hence, we used 8/12 of the 2012 estimate within the INFLUX domain and arrive at 2.3 MtC, again, nearly identical to the Hestia onroad $FFCO_2$ estimate of 2.24 MtC. It is worth noting that the two estimates (Hestia and DARTE) have different spatial distribution but similar total domain emissions.

Electricity production: The INFLUX domain includes 12 electricity production facilities that were operational in 2012/2013. Emissions from six of these facilities were retrieved from the Environmental Protection Agency Clean Air Markets Division (CAMD) data reporting, three were retrieved from the Energy Information Administration (EIA) reporting and three reported through the National Emissions Inventory. The relative magnitude of these three sets of emissions reporting were 1.36, 0.001, and 0.003 MtC/yr in the year 2012. As described in Gurney et al. (2016), there are multiple datasets in the United States with independently derived estimates of CO_2 emissions from US power plants. Many of these facilities were found to have large differences in monthly estimated

Table 1: Alternative estimates of the onroad $FFCO_2$ emissions for the September 1, 2012 to April 30, 2013 period in the INFLUX domain. DOI: https://doi.org/10.1525/elementa.137.t1

Onroad $FFCO_2$ approach	Estimation technique	Key parameters	Onroad $FFCO_2$ (MtC)	Reference
Hestia	VMT, fleet stats, emission factors	MOVES output, AADT, basemap segment length	2.24	Gurney et al., 2012; USEPA 2015
Statewide fuel	Pop proportion	Onroad gasoline & diesel fuel sales/consumption, 2012/2013 population	1.79	USDOE 2016, US Census 2016
Statewide fuel	Retail sales proportion	Onroad gasoline & diesel fuel sales/consumption, 2012 retail sales	2.25	USDOE 2016, US Census 2016
DARTE	Alternative bottom up		2.31	Gately et al., 2015

$FFCO_2$ emissions when two of the largest datasets were compared (*Gurney et al.*, 2016).

The six facilities reported here as using the CAMD data also report through the EIA allowing for a comparison of reporting. These six facilities account for 99.7% of the electricity production $FFCO_2$ emissions in the INFLUX domain. However, the difference between the CAMD data and the EIA reporting were small, amounting to 0.014 MtC/yr and show the CAMD reporting as the larger of the two, the data source used in the Hestia $FFCO_2$ emissions data product. Hence, the potential for differences is small and in a direction contrary to the hypothesized underestimate.

Hestia Version 3.0: Since the release of the Hestia $FFCO_2$ emissions estimate for the INFLUX inversion effort (version 2.0), updates to a few of the key data sources have become available enabling a version 3.0 of the data product.

Figure 2 presents a pie chart representation of the version 3.0 2011 $FFCO_2$ emissions. As with version 2.0, emissions in Marion County are dominated by the onroad and electricity production sector emissions. The latter is driven by the Harding Street Station, accounting for almost 90% of the electricity production $FFCO_2$ emissions in the year 2011.

Table 2 shows comparison of the Hestia version 2.0 versus version 3.0 $FFCO_2$ annual emissions for Marion County only (the largest county emitter in the INFLUX domain) for the economic sectors and across the 2011–2014 time period. Total $FFCO_2$ emissions for 2011 are nearly unchanged, though there were canceling sectoral changes. In particular, the residential and commercial sector emissions are larger in version 3.0 but the industrial sector emissions were less and compensatorially so. Emissions in 2012 show an increase in total emissions for version 3.0 (from 4.07 to 4.15 MtC/yr) driven primarily by the increase in residential and commercial emissions that were less compensated for by the smaller industrial emissions in version 3.0. The estimate for 2013 decreased by a small amount (from 4.32 to 4.26 MtC/yr) and was mostly driven by the lesser industrial sector emissions. A representative difference for the eight-month period from September 2012 to April 2013 is 0.007 MtC.

It is worth noting that the spatial distribution of the fluxes differs between version 2.0 and 3.0, owing to significant differences in the road basemap used and the new spatial footprint of the nonroad $FFCO_2$ emissions. There is also some spatial difference due to a different proportion of residential, commercial and industrial building emissions. **Figure 3** shows the spatial distribution of $FFCO_2$ emissions in Marion County for the year 2011. The residential, commercial and onroad sectors in addition to the county total are shown. **Figure 4** presents the percentage difference between the version 2.0 and version 3.0 products for the same sectors as **Figure 3**.

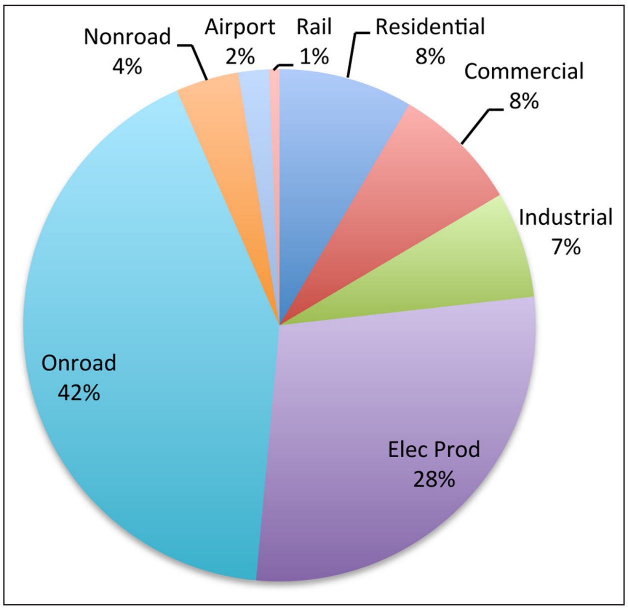

Figure 2: Hestia $FFCO_2$ emissions for Marion County, Indiana. Proportion of the total 2011 Hestia version 3.0 $FFCO_2$ emissions for Marion County, Indiana from each of the eight sectors. DOI: https://doi.org/10.1525/elementa.137.f2

3.2.2 Missing CO_2 emissions

There are some categories of emissions within the INFLUX domain that are not associated with the combustion of fossil fuel and these could contribute to the 0.94 MtC difference. Because the atmospheric CO_2 inversion infers the total CO_2 flux within the domain, there is the potential for vegetation and soil carbon exchange to be reflected in the inversion posterior flux estimate but not included in

Table 2: $FFCO_2$ emissions, categorized by sector, comparing Hestia version 2.0 to version 3.0 for Marion County, Indiana, 2011, 2012, and 2013. Units: MtC/yr. DOI: https://doi.org/10.1525/elementa.137.t2

Year/version	Resid	Comm	Ind	Elec Prod	Onroad	Nonroad	Airport	Rail	Total
2011 Version 2.0	0.30	0.29	0.44	1.14	1.70	0.16	0.049	0.010	**4.09**
2011 Version 3.0	0.34	0.33	0.27	1.14	1.70	0.16	0.078	0.026	**4.05**
2012 Version 2.0	0.26	0.27	0.44	1.18	1.70	0.16	0.048	0.011	**4.07**
2012 Version 3.0	0.30	0.38	0.32	1.18	1.70	0.15	0.077	0.029	**4.15**
2013 Version 2.0	0.32	0.32	0.45	1.30	1.70	0.16	0.047	0.011	**4.32**
2013 Version 3.0	0.31	0.32	0.29	1.30	1.72	0.15	0.075	0.099	**4.26**

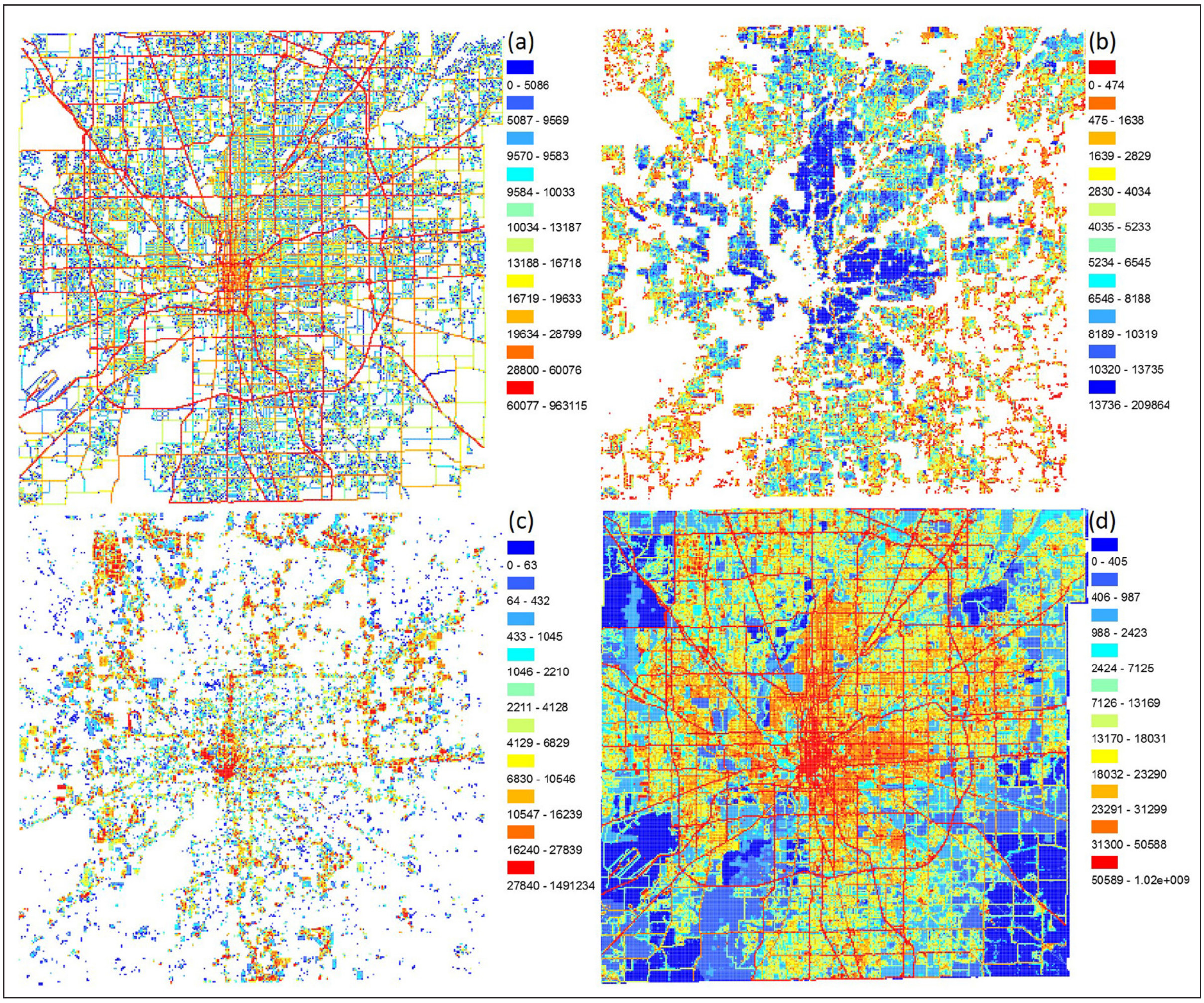

Figure 3: Map of gridded $FFCO_2$ emissions. Marion County, Indiana 2011 $FFCO_2$ emissions from the Hestia version 3.0 gridded at 100 meter × 100 meter resolution for the **a)** onroad sector; **b)** residential sector; **c)** commercial sector; **d)** total emissions. The color bar scales are different in each panel. Units: kgC/yr/grid cell. DOI: https://doi.org/10.1525/elementa.137.f3

the prior flux. Similarly, human/animal respiration occurs within the domain and is most likely driven by imported carbon embedded in food. Hence, these heterotrophic respiration fluxes would be reflected in the atmospheric inversion flux but not included in the Hestia prior $FFCO_2$ flux. We consider both categories of "missing" flux and estimate their magnitudes.

Animal respiration: Respiration from humans and other animals within the INFLUX domain could be a contributor to the difference between the inversion and Hestia $FFCO_2$ emissions flux estimates. For the purposes of simplicity, we consider only respiration emanating from the human population and domestic pets for which there is statistical information. Wild fauna are not considered. We also assume that all food consumed by humans and pets within the domain is imported from locations outside the domain and the CO_2 uptake associated with the vegetation consumed directly or indirectly through consumption of animal products is not accounted for in the atmospheric inversion. Since the eight counties surrounding Marion

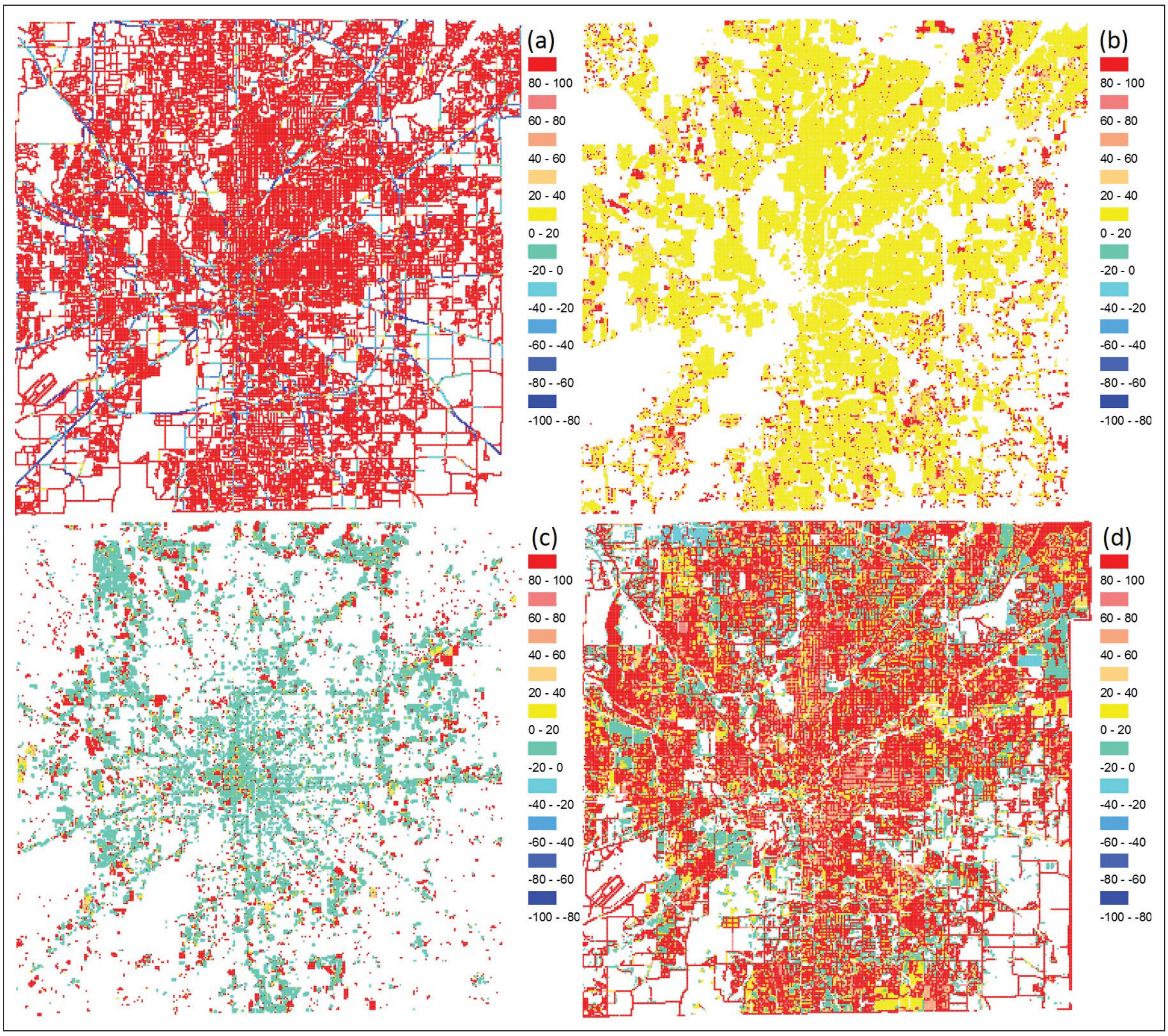

Figure 4: Map of gridded $FFCO_2$ emissions percent difference. Marion County, Indiana 2011 $FFCO_2$ emissions difference between the Hestia version 2.0 and Hestia version 3.0 at 100 meter × 100 meter resolution for the **a)** onroad sector; **b)** residential sector; **c)** commercial sector; **d)** total emissions. Units: percent. DOI: https://doi.org/10.1525/elementa.137.f4

County do engage in agricultural activity, this assumption is flawed to some degree. However, given research indicating that the average travel distance of fruits and vegetables traded in Chicago is greater than 1500 miles, this assumption is reasonable (*Pirog et al.*, 2001).

Assuming an average CO_2 exhalation rate of 254 gC/person/day and a 2012/2013 population in the portion of the nine counties in the INFLUX domain of 1,878,546, the average generation of CO_2 due to human respiration, scaled to the eight-month interval (8/12), is 0.12 MtC. (*US Census*, 2016; *Prairie and Duarte*, 2007). This is similar in magnitude to a similar estimate made in Turnbull et al. (2015). Assuming dog and cat ownership in the INFLUX domain follows the US national average, 0.22 dog/person and 0.24 cat/person, and the CO_2 exhalation rate is roughly 25% that of humans based on mean dog/cat body mass and allometric relationships, an additional 0.014 MtC must be added to human respiration for a total contribution of 0.13 MtC during the September 2012–April 2013 period (*AVMA*, 2012; *Prairie and Duarte*, 2007).

Biotic combustion: Because the Hestia data product only captures combustion of fossil fuel, the combustion of biotic fuel could constitute a source of emissions missing from the prior flux but captured in the measured CO_2 mixing ratios. The Covanta Indianapolis Energy facility located in Marion County burns municipal solid waste of biogenic origin to generate electricity. The Hestia $FFCO_2$ emissions data product does not include any emissions derived from biological material. Hence, the difference between the fluxes inferred from monitored CO_2, which does include biologically-derived CO_2, and the Hestia emissions could be due to this difference. The Covanta facility reported 0.095 MtC during the September 2012 to April 2013 period. Hence, this could be a contributing factor to the 0.94 MtC difference.

A similar category of emissions that is part of the combustion associated with human activities is the use of biotic material for home heating such as woodstoves or wood-burning fireplaces. We approximate this category of emission by using the EPA estimated U.S. total

CO_2 emissions from wood combustion in the residential sector. With a mean U.S. per capita figure, the application of this emission rate to the population within the INFLUX domain comes to approximately 0.05 MtC during the eight-month period in question. This is likely an upper limit on this emission amount since some of the combustion material could be sourced to growth within the INFLUX domain and hence, technically only a portion of the complete gross flux. As with yard/leaf waste that is often burned, there is an offset in time – growth and uptake is temporally separated from the time of combustion. However, the magnitude of this emission amount is too small to be of concern for present purposes.

Biofuel is used within the onroad sector as a component of gasoline. Because the Hestia system estimates onroad $FFCO_2$ using an activity-based approach (i.e. using vehicle miles traveled), this emission of CO_2 is reflected in our $FFCO_2$ emission in the onroad sector, but not tracked separately.

Biosphere respiration: Were the net biosphere exchange to be a positive flux (from the land to the atmosphere), this would result in a positive adjustment to the Hestia $FFCO_2$ emissions estimate. A positive biosphere carbon exchange might be expected from a biological system in which the absolute magnitude of the gross respiration flux exceeded the absolute magnitude of the gross photosynthetic flux. Though not expected during the growing season, where photosynthesis typically dominates the net exchange in mid-latitude vegetation, a positive net exchange may occur during the initial and ending months of the September – April period over which the INFLUX flux inversion operated.

There is little research aimed at quantifying respiration fluxes in urban areas, particularly during months outside the growing season. We draw from three studies that measured urban respiration fluxes in U.S. cities at times of the year coincident with the September-April period of the INFLUX inversion (*Decina et al.*, 2016; *Kaye et al.*, 2005; *Chen et al.*, 2014). The three studies performed measurements in Boston MA, Fort Collins CO, and Baltimore MD. The studies also sampled different urban land cover types but all reflected cover types with either bare soil, grass or forest cover. The fluxes vary by year sampled, month sampled, and land cover type and ranged from near-zero (In December/January) to 4 moles CO_2/m2/s. For the rough estimation purposes here we take a conservative estimate from this range of 0.5 – 1 mole CO_2/m2/s. We also apply this flux to an estimate of pervious surface area within each of the nine INFLUX counties using an estimate of remotely sensed built-up area (*Pesaresi et al.*, 2015). We assume this area is predominantly grass land cover. Finally, we only apply this respiration flux rate to those days within the September 2012 – April 2013 period for which there were three consecutive days with a 24 hour mean temperature above 32°F and use soil/grass temperature measurements from the West Lafayette IN airport meteorological station (*Indiana State Climate Office*, 2016). Out of these 209 days, 52 days (January 19 – March 11) qualified as having a soil/grass daily mean temperature consistently below 32°F. With a respiration flux of 1 mole CO_2/m2/s we arrive at a total flux in the domain over this time period of 0.58 – 1.17 MtC.

Indeed, Figure 8 of Lauvaux et al., shows the difference between the Hestia $FFCO_2$ prior flux and the inverted flux at a minimum during the early part of 2013, precisely when the respiration fluxes are at a minimum, coinciding with the lowest ground temperatures of the year.

Figure 5 summarizes both the potential biases in the Hestia $FFCO_2$ emissions estimate and the missing CO_2 fluxes reviewed here. The lower end of the final range of the INFLUX emissions accounted for here in attempting to reconcile the bottom-up and top-down comes to 5.25 MtC while the upper end of the range is 6.12 MtC. The median of the inverse-estimated range, 5.50 MtC, is within the constructed flux range. Though this can only be considered a rough and approximate estimate of the potential differences, the potential difference appears reasonably explained by the hypotheses presented with respiration from the urban biosphere the largest and most significant component in the difference estimate.

4. Discussion and conclusions

This study identifies and quantifies key uncertainties and CO_2 fluxes to account for the disparity between the central estimate of the Lauvaux et al. (2016) atmospheric CO_2 inversion study and the Hestia bottom-up $FFCO_2$ emissions estimate for the INFLUX domain. We examined errors in the Hestia $FFCO_2$ emissions estimate itself and an assessment of missing CO_2 flux sources.

Within the first category, the electricity production sector and the onroad vehicle sector are the most likely candidates given their relative magnitude in the INFLUX domain. Two different reporting streams associated with U.S. power plants show consistency in the INFLUX domain although these two datasets show large differences in some other U.S. locations. Different approaches to estimating onroad vehicle $FFCO_2$ emissions indicate the potential for error. However, of the few alternative approaches to estimating onroad emissions explored here, the Hestia onroad vehicle $FFCO_2$ emissions estimate remains one of the highest, making it less likely to contribute to the 0.94 MtC deficit between the larger inverse estimated flux and Hestia $FFCO_2$ emissions. However, given the challenges of estimating onroad $FFCO_2$ emissions from the bottom-up, the onroad sector must remain a potential source of bias in the comparison.

Three flux categories were explored that were potentially reflected in the inverse-estimated flux but not present in the Hestia $FFCO_2$ flux estimate, by design. The use of biotic fuels in electricity generation is tallied by US agencies but not included in the Hestia system. In the INFLUX domain, the amount of biotic fuel used to generate electricity is small. Similarly, biotic material burned in residential woodstoves and fireplaces is likely too small to be of much consequence. Respiration by both animals and soils/vegetation was considered and of the two, the potential for soil/vegetation respiration is larger by roughly an order of magnitude. Hence, though each of the potential corrections noted here may play a role, the magnitude of soil/vegetation respiration is

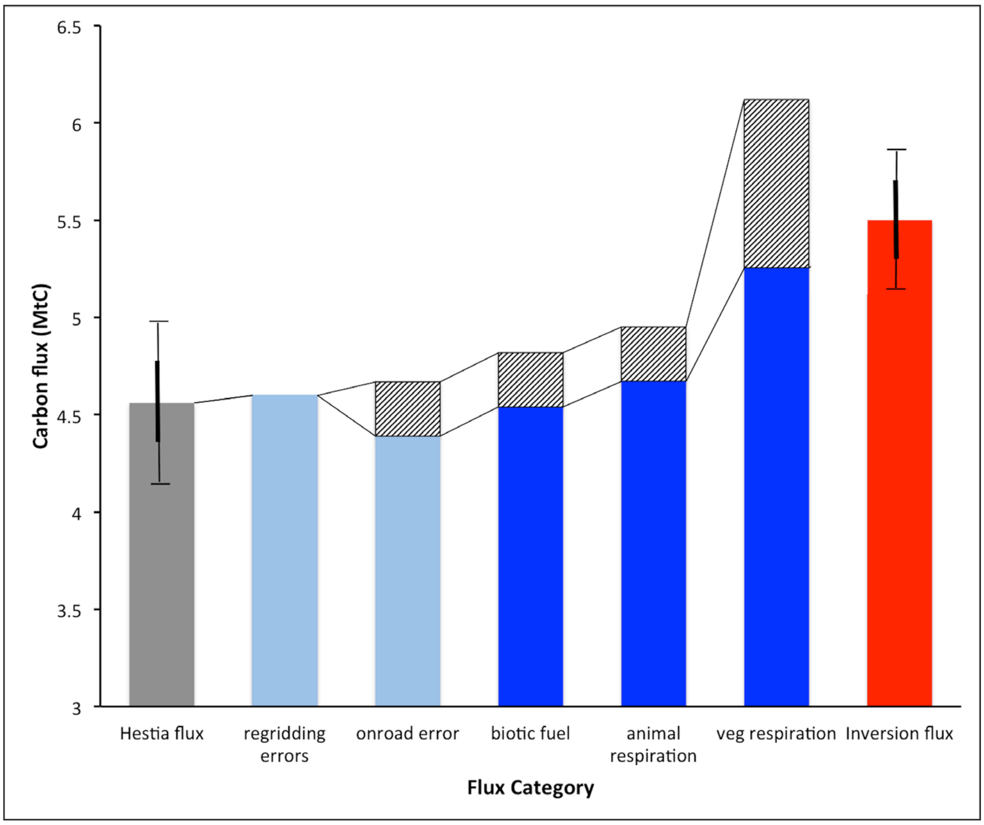

Figure 5: Reconciliation of the INFLUX CO_2 emissions. The Hestia $FFCO_2$ flux estimate and uncertainties (thick line: one-sigma; thin line: 2-sigma), the individual CO_2 flux reconciliation adjustments, and the reference inversion CO_2 flux estimate and uncertainties (thick line: one-sigma; thin line: 2-sigma) for the September 1, 2012 to April 30, 2013 period in the INFLUX domain. The adjustments to the Hestia $FFCO_2$ flux estimate are cumulative from left to right, and the hatched region denotes the range of values associated with the cumulative flux adjustment. Light blue columns represent $FFCO_2$ errors; dark blue columns represent missing CO_2 fluxes. Units: MtC. DOI: https://doi.org/10.1525/elementa.137.f5

potentially large enough to singularly explain the disparity. The research community is aware of the potential for soil/vegetation respiration outside the growing season to contribute to observed CO_2 mixing ratios, but empirical evidence in the urban domain has been limited. Only recently have there been measurements within mid-latitude urban areas to support the notion that the flux may be large enough to warrant explicit inclusion (*Decina et al.*, 2016; *Kaye et al.*, 2005; *Chen et al.*, 2014). Indeed, the soil/vegetation covered landscape within the urban domain tends to be heavily managed with both water and soil nutrients available throughout the year (*Kaye et al.*, 2006). The potential for soil/vegetation respiration to influence measured CO_2 mixing ratios emphasizes the need to consider the fact that the urban biosphere will continue to be active outside times of the year when photosynthesis and/or net uptake is dominant. We conclude that this missing flux can account for nearly all of the discrepancy between the two approaches to within statistical uncertainty, reconciling the bottom-up Hestia $FFCO_2$ estimate with the inversion-based estimate in the INFLUX domain.

Though missing respiration fluxes is the most obvious explanation for the discrepancy, the simplicity of the exploration here does not eliminate a biased bottom-up emissions data product as a potential factor in the disparity with the inverse-estimated posterior flux. The alternative approaches to estimating the larger contributors to the fossil fuel budget remain limited and hence, cannot be considered conclusive proof that the Hestia data product is not biased. Ideally, improved empirical data and associated uncertainties are required to improve bottom-up estimation of fluxes. Some superior data do exist which would allow for better estimates of $FFCO_2$ emissions from the bottom-up. For example, household utility billing data, though not without measurement uncertainty, offers a direct measured estimate of on-site building emissions. Legal barriers and privacy concerns prevent this information from being shared outside of energy supply utilities and their ratepayers. Arrangements whereby utility billing data is anonymized or aggregated to scales that eliminate privacy concerns should be pursued and standardized (*Pincetl et al.*, 2015). Even representative samples in specific urban domains would improve the estimation algorithms in the building sector.

Onroad vehicle $FFCO_2$ emissions, often the largest single emitting sector in US cities, presents unique data challenges because of its mobile nature. Nevertheless, more comprehensive traffic monitoring and vehicle fleet information from inspection/maintenance recordkeeping could improve the onroad $FFCO_2$ emissions estimate. This information is available in some cities, but standardization and comprehensive coverage is sorely needed.

There are also techniques that assist in making the top-down and bottom-up approaches more consistent in terms of the categorical fluxes estimated. The use of $^{14}CO_2$ measurements as a near-ideal tracer for the fossil fuel component of CO_2 fluxes in urban areas is a powerful way to assist in parsing the budget between the biological and fossil carbon pools (*Miller et al.*, 2012, *Turnbull et al.*, 2006). For linear tracers such as CO_2, inversion systems can incorporate components of CO_2 fluxes as separate tracers, supplying each with unique prior and posterior fluxes (*Enting*, 2002).

Observations of $^{14}CO_2$ have been collected in the INFLUX domain and conclusions elaborated in the work of Turnbull et al. (2015). The results here are consistent with the observed ratios of wintertime urban-enhanced total CO_2 to the fossil fuel-derived component associated with the $^{14}CO_2$ measurements. They found an approximate 20% enhancement of wintertime CO_2 above the fossil fuel-derived CO_2 when using all the measurement towers in the INFLUX domain (*Turnbull et al.*, 2015: **Table 2**, row 5). Though not conclusive proof given the inherent uncertainties and the difficulty of fully eliminating the background inflow of air, the 20% enhancements are nearly identical to the discrepancy between the Hestia $FFCO_2$ flux and the reference inversion posterior flux result and consistent with the reconciliation found here.

Given the importance and estimated magnitude of the biosphere respiration flux as estimated here, an important future task in closing the budget over the INFLUX domain is assessment of the soil/vegetation flux through a combination of direct measurement, land cover and ecosystem modeling.

Data Accessibility Statement
Hestia version 2.0 & 3.0 results can be retrieved from hestia.project.asu.edu/audience_researchers.shtml.

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- Contributed to conception and design: KRG
- Contributed to acquisition of data: JL, DO, RP, MH, PS, JT
- Contributed to modeling results: KRG, JL, JH, RP, TL
- Contributed to analysis and interpretation: KRG
- Drafted and/or revised article: KRG, JT, TL
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