Urban eddy-covariance: Why, how and where?

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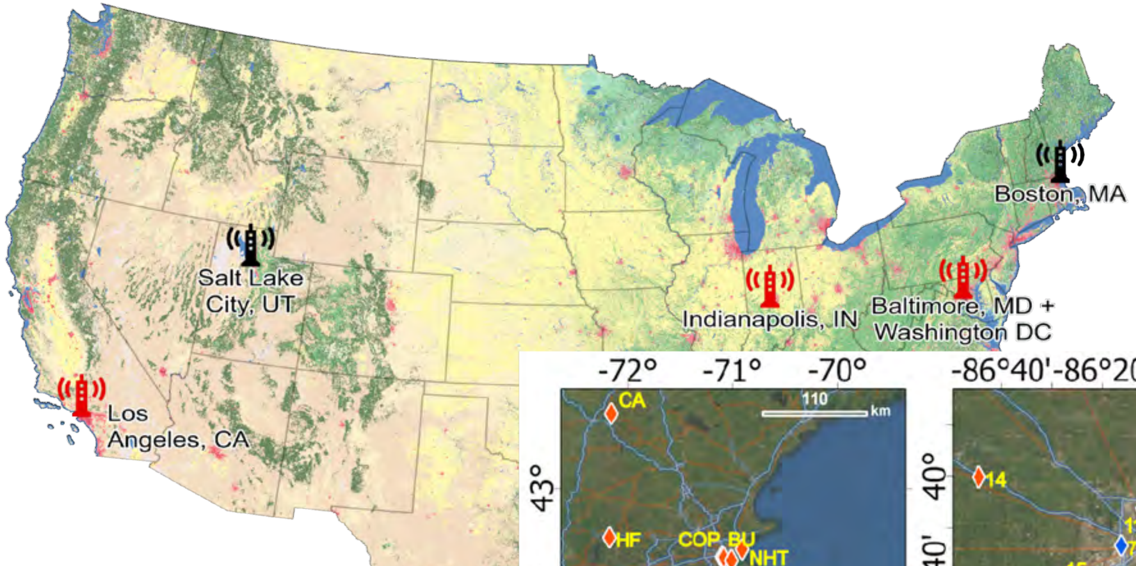
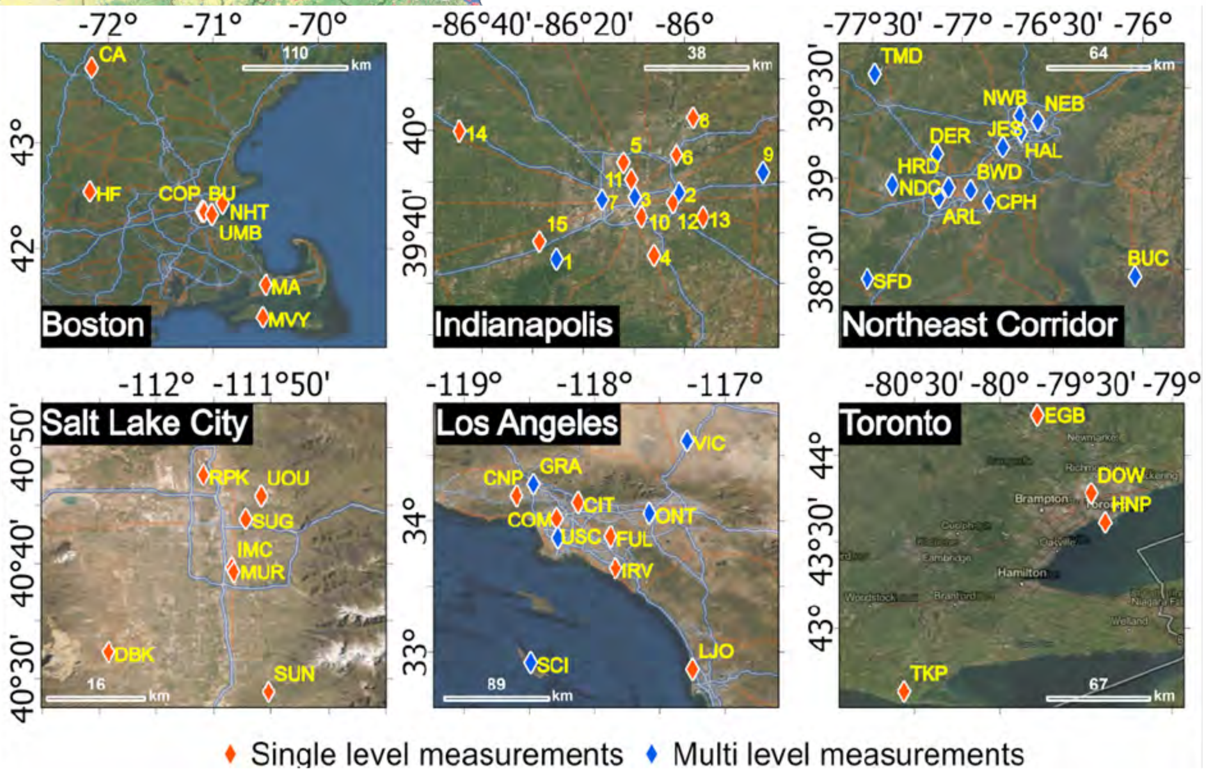
Urban GHG emissions studies in the US are dominated by atmospheric inversions

Red cities are NIST urban test-beds

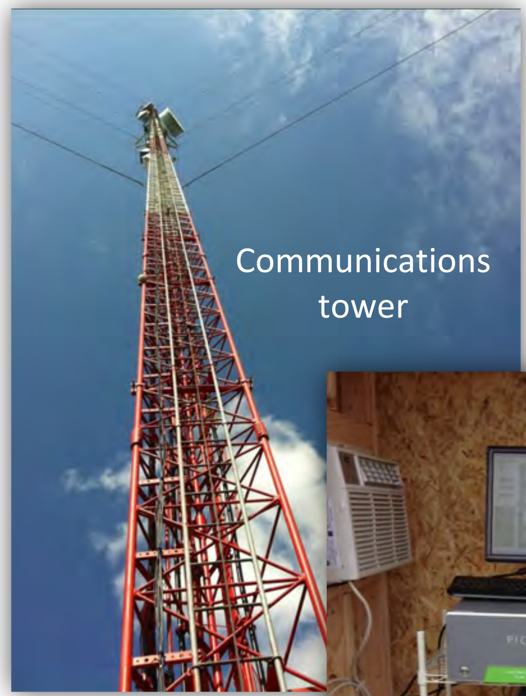


Measure GHG enhancements caused by urban fluxes (Miles et al., 2017).

Solve for emissions using atmospheric budgets (Heimburger et al., 2017); or inversions (Lauvaux et al, 2020).



Maps courtesy of Vanessa Monteiro



Picarro cavity ring-down spectrometer and calibration tank.

Continuous measurements of GHG

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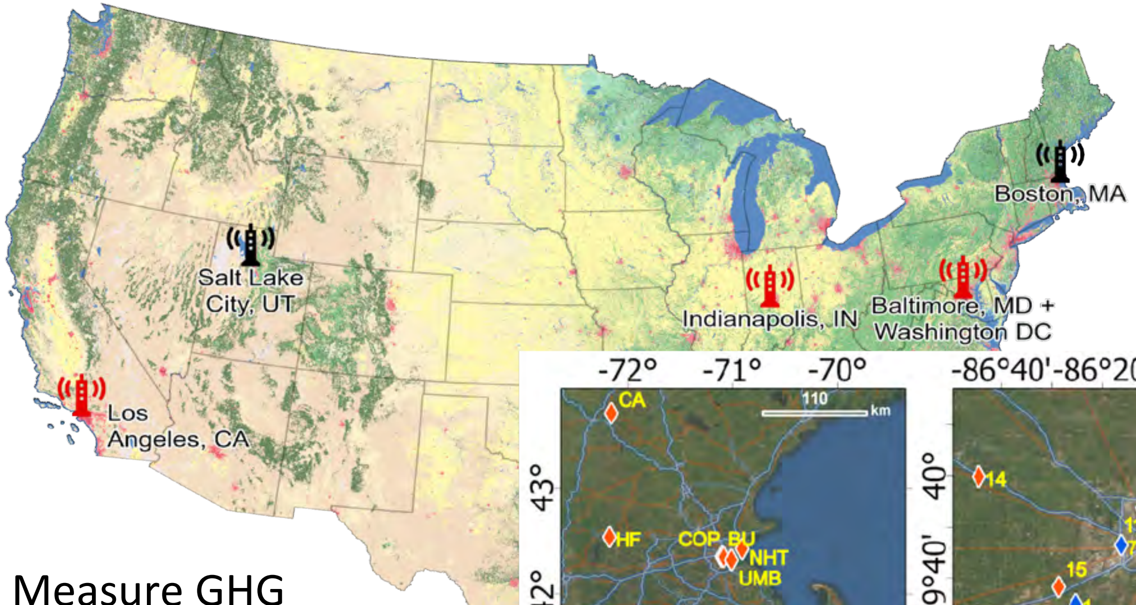

What about flux towers?

How can they be used to complement urban GHG studies?

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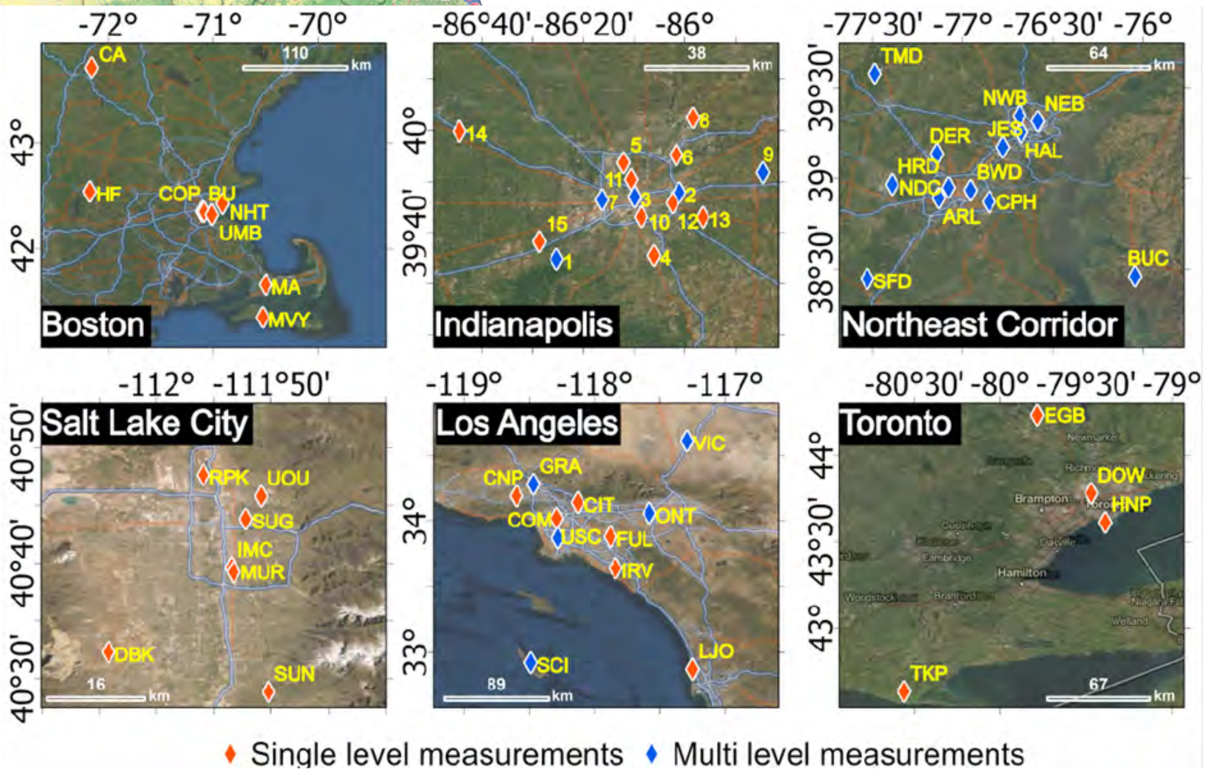

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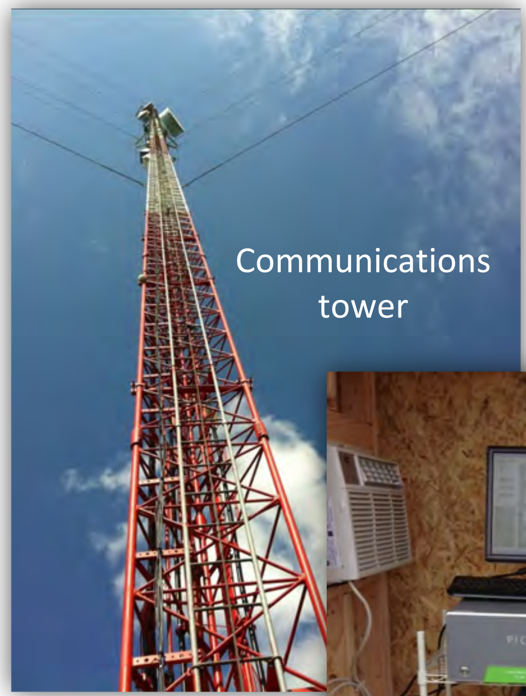

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Continuous measurements of GHG

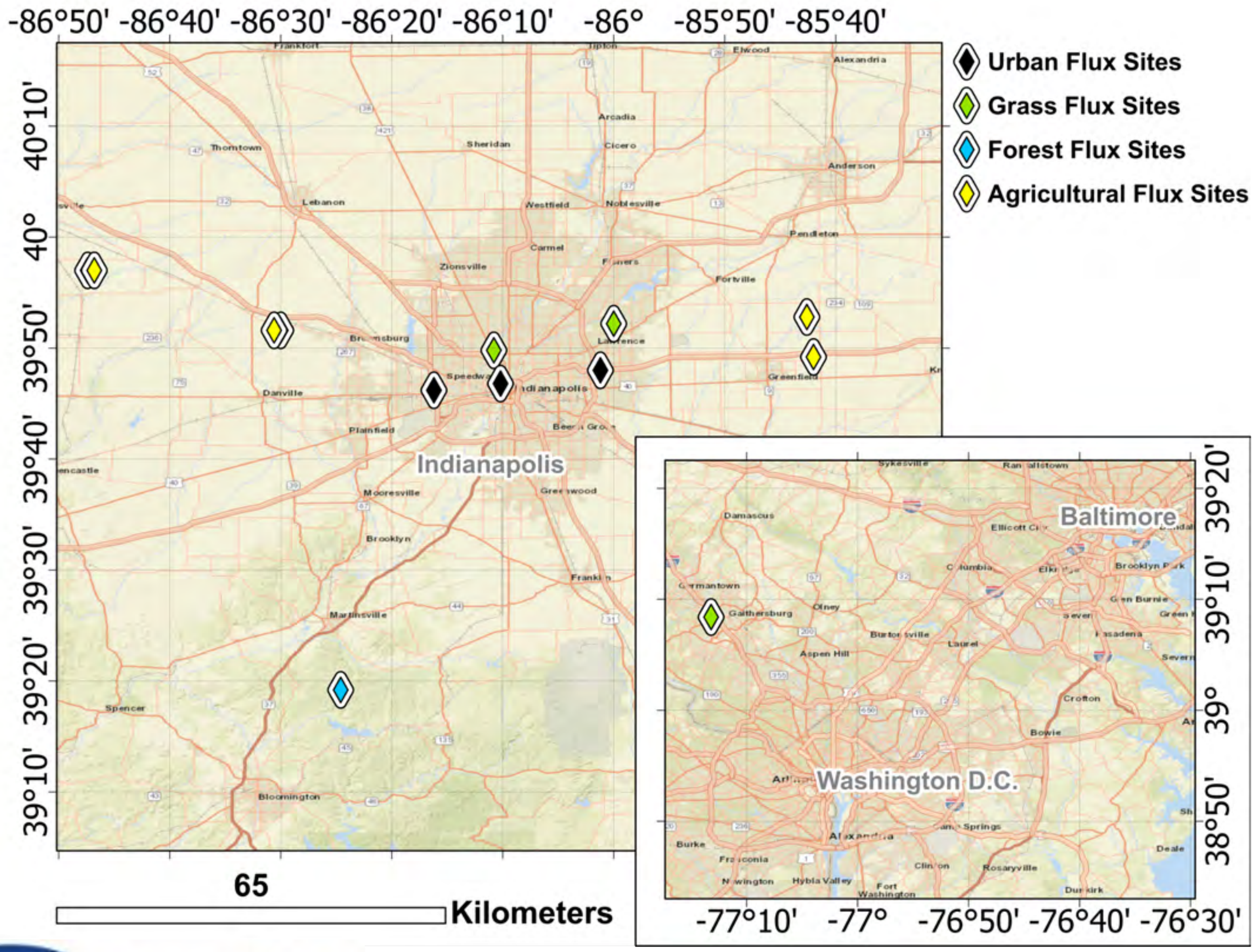
Urban eddy covariance: Why?

- Same purpose as ecosystem flux towers.
  - Measure fluxes continuously, and at high resolution in space and time.
  - Collect ancillary data required to test process-level understanding.
  - Develop, evaluate and improve process-based flux models that we can then extrapolate over space and time.
- A component of "bottom up."
- Merge with "top down" (atmospheric inversions/budgets) to quantify city-wide GHG fluxes.
- Aren't urban systems too complex for flux towers? *No.*
- Can we prove it? *Yes.*

Objectives / demonstrations.
And insights as we go into “how” and “where”

- We need to evaluate our process-level understanding of anthropogenic GHG emissions (e.g. Gurney et al, 2012) with observations. *Wu et al, submitted.*
- We need to understand urban *region* ecosystem GHG fluxes. They confound our understanding of anthropogenic emissions (Wu et al., 2018; Miles et al, 2021), and they are interesting in their own right.
    - Urban ecosystems
    - Rural background
- We can use urban eddy covariance to evaluate the momentum and buoyancy fluxes driving urban ABL simulations (Sarmiento et al., 2017).

Penn State / NIST / AmeriFlux urban flux tower network: Indianapolis and the NEC



- Urban, Turf Grass, and Agricultural sites deployed.
- MMSF forest data also used.
- Many sites have been deployed for limited time periods.
- We currently have five flux systems in operation.
- Details and applications to follow

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Don’t urban atmospheric inversions test urban inventories? Why flux towers?

- Do we use continental inverse models to evaluate our ecosystem biogeochemical models?
- We might compare large-area net annual or seasonal fluxes (e.g. SOCCR2), but when we want to understand the processes in our ecosystem models, we often turn to flux towers.

Don’t urban atmospheric inversions test urban inventories? Why flux towers?

- Do we use continental inverse models to evaluate our ecosystem biogeochemical models?
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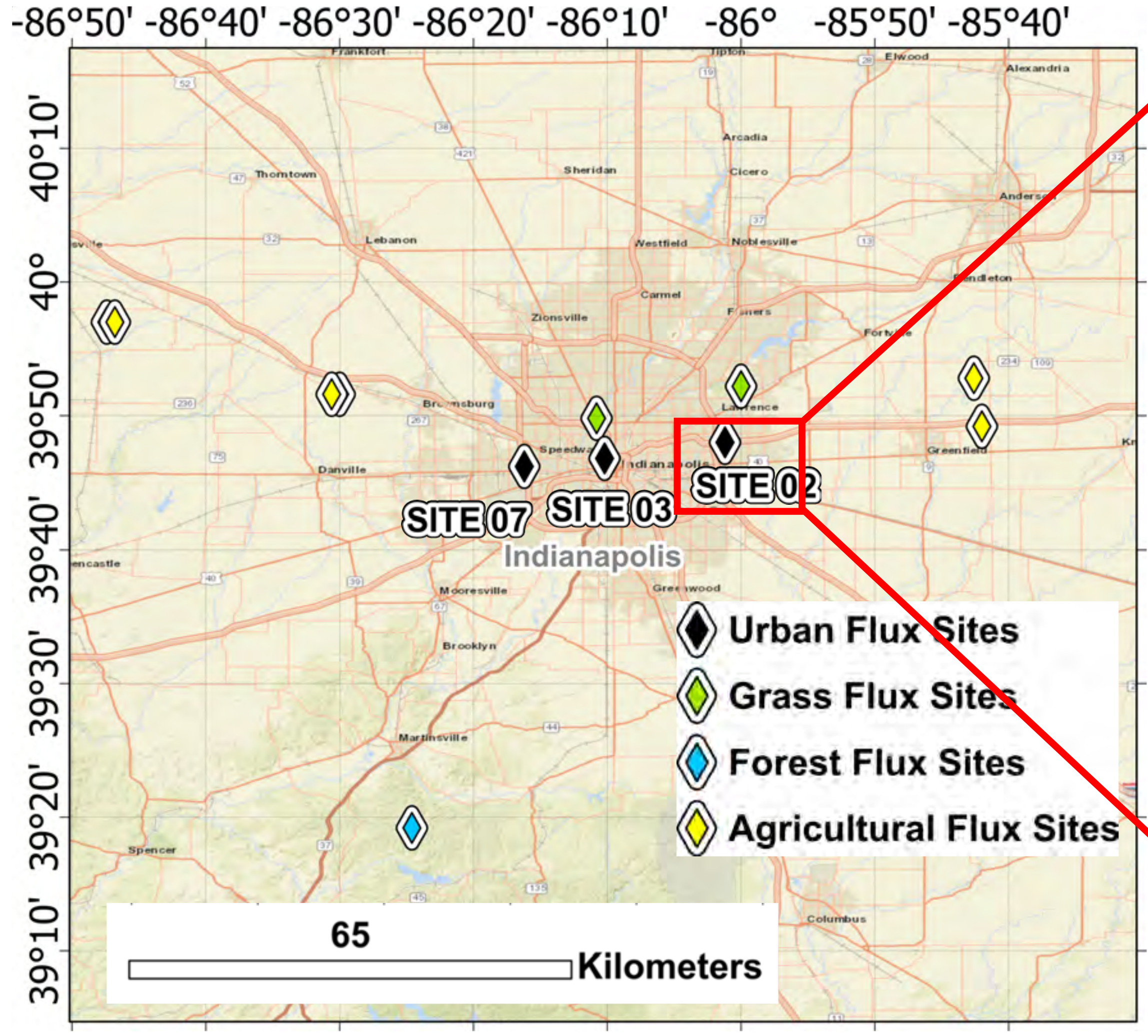
- Why flux towers? High spatial and temporal resolution.
- Why atmospheric inversions? They encompass the whole city.

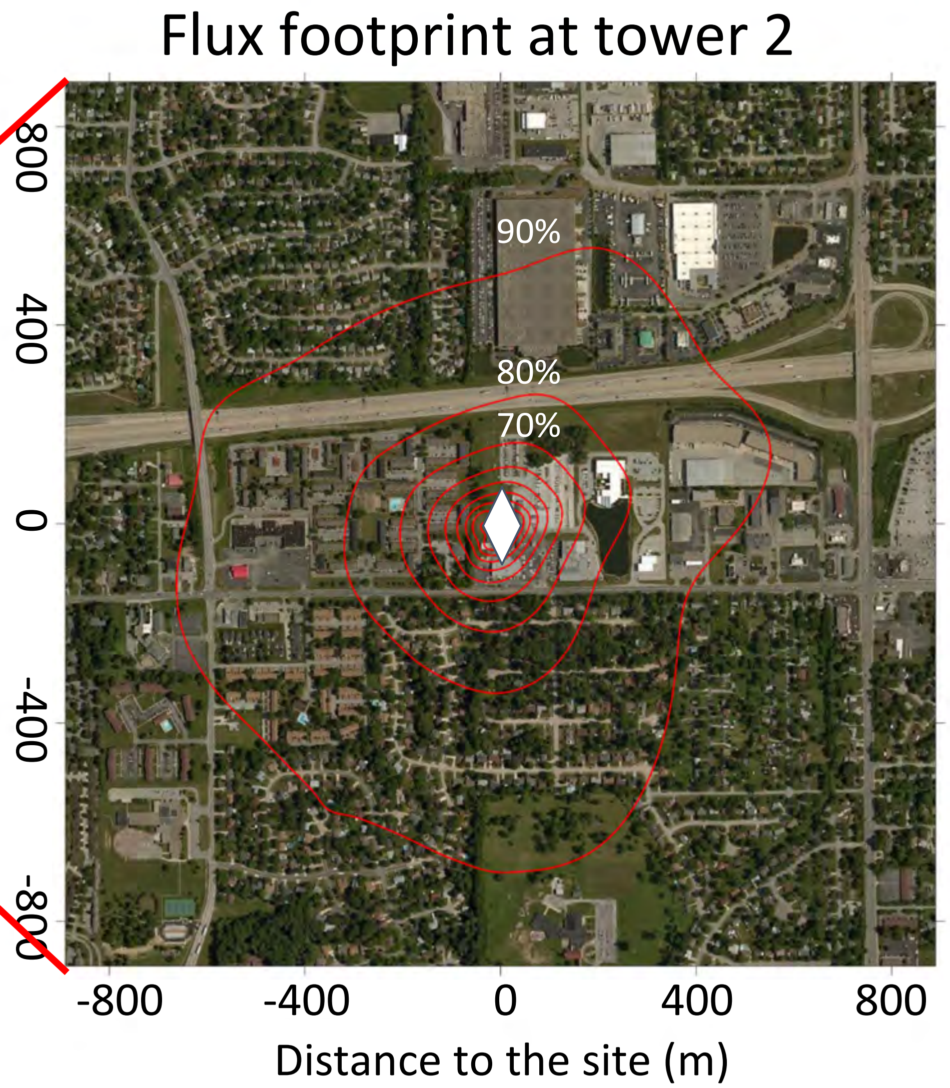
Objectives / demonstrations.
And insights as we go into "how" and "where"

- We need to evaluate our process-level understanding of anthropogenic GHG emissions (e.g. Gurney et al, 2012) with observations. *Wu et al, submitted.*

- Which anthropogenic GHG emissions model?
  - Hestia (Gurney et al, 2012) offers 1 km^2 resolution, hourly, sector-specific urban emissions.
  - Hestia has been compared to urban inversions (Turnbull et al., 2019; Lauvaux et al, 2020) with very good success.
  - The high spatial and temporal resolution, process-level fluxes from Hestia have not previously been compared to atmospheric flux observations.

Decomposition of flux measurements: Hestia - EC comparison

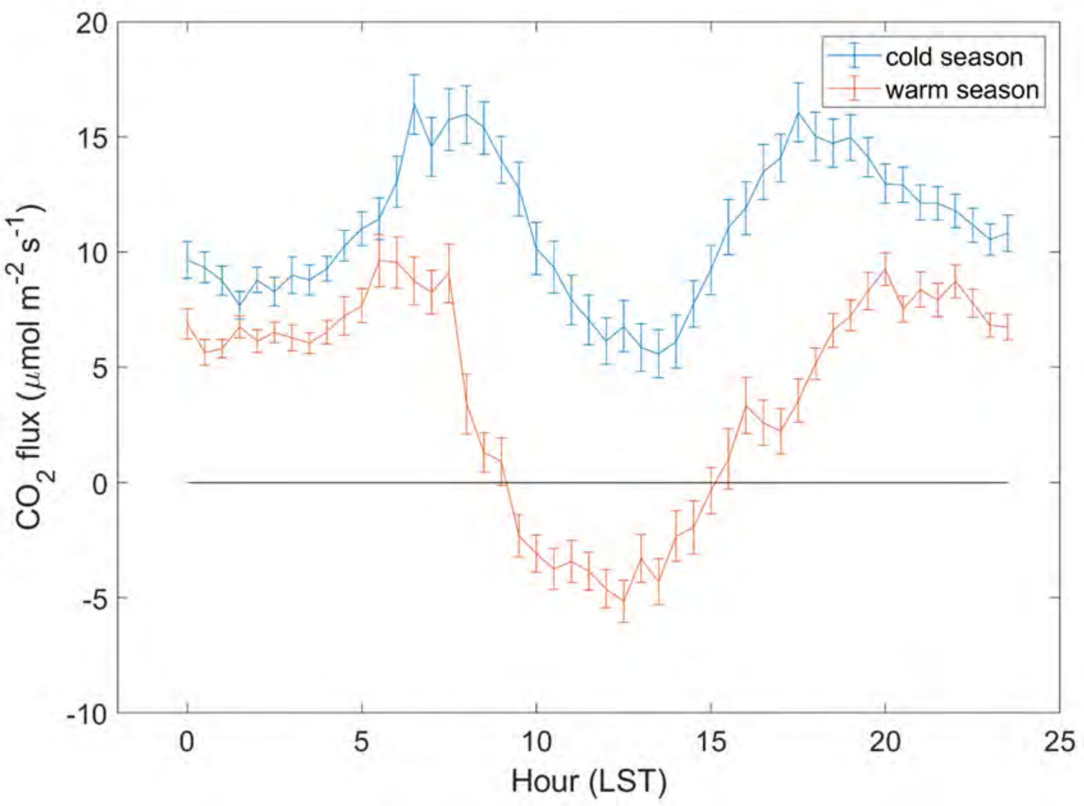




- Mixed suburban environment
- Communications tower
- Three-level $CO/CO_2/CH_4$ profile (10, 40, 136m AGL)
- Flux instrumentation at 30 m AGL
- Flux system operated for about seven months.

Wu et al, submitted.

Flux data show expected patterns for mixed biological and anthropogenic CO_2 fluxes



Cold season (JFM): traffic emissions and domestic heating

Warm season (AMJJ): photosynthesis, respiration, and CO_2ff emissions.

Total CO_2 fluxes look very reasonable in time:

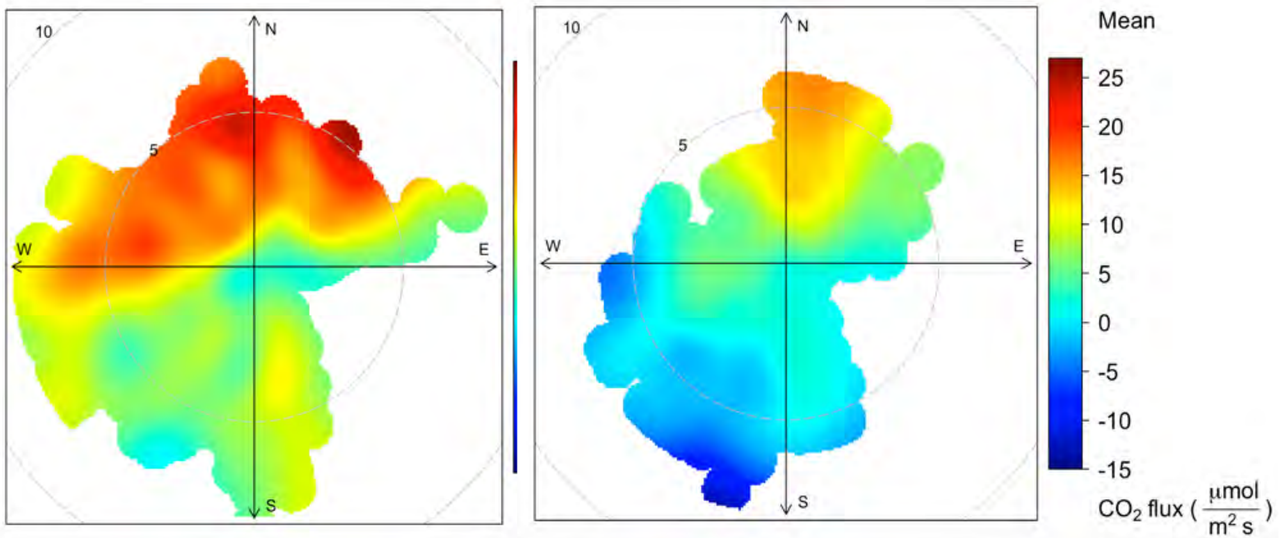
- Traffic peaks at rush hours
- Biological flux contributions in the summer.

And in space:

- Fluxes are large and positive from the north (highway), and
- smaller, sometimes negative from the south (suburban, vegetation).

Cold season (JFM)

Warm season (AMJJ)



- But these are total CO_2 fluxes. We can't compare these directly to Hestia.
- We can do better…

- We decompose fluxes into biological and anthropogenic components using CO/CO_2 ratios,
- and decompose the anthropogenic fluxes in space to match Hestia pixel by pixel using a flux footprint model.

- Then we can construct an "apples to apples" test of Hestia vs. EC fluxes…
  - total CO_2ff emissions,
  - temporal pattern of emissions,
  - spatial pattern of emissions

Methods: disaggregate fossil fuel and biogenic CO_2 fluxes

Flux-gradient relation: surface flux (F) is equal to the product of eddy diffusivity parameter (K) and the mean vertical CO_2 mole fraction gradient (∇C): $F = -K \times \frac{\partial c}{\partial z}$

Eddy diffusivity (K) → CO fluxes (F_{CO}) → Fossil fuel CO_2 emissions (F_{CO2ff}) → Biogenic CO_2 fluxes (F_{CO2bio})

$$\hat{K} = -\frac{F_{CO2}}{\nabla C_{CO2}}$$

$$\hat{F}_{CO} = -\hat{K}\nabla C_{CO}$$

$$\hat{F}_{CO2ff} = \frac{\hat{F}_{CO}}{R}$$

$$\hat{F}_{CO2bio} = F_{CO2} - \hat{F}_{CO2ff}$$

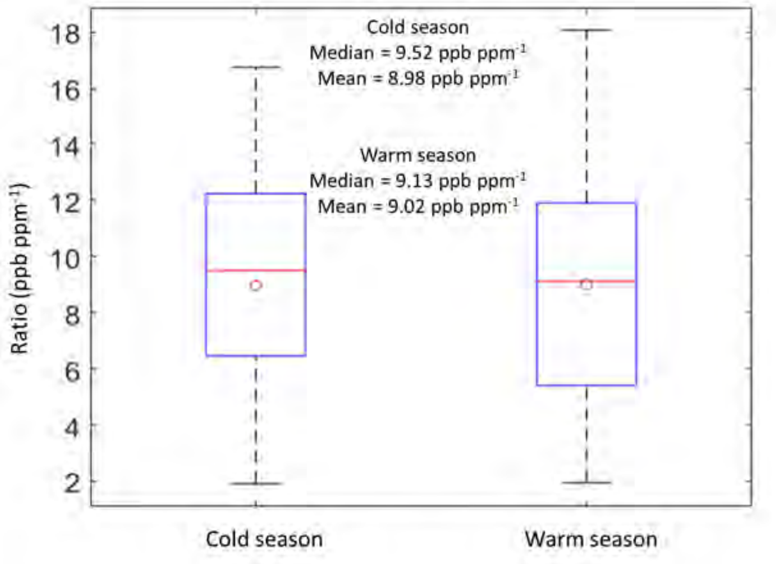
Assumptions:

- Eddies contributing to flux measurement are locally generated
- CO and CO_2 have similar vertical mixing process (same eddy diffusivity)

Data screening:

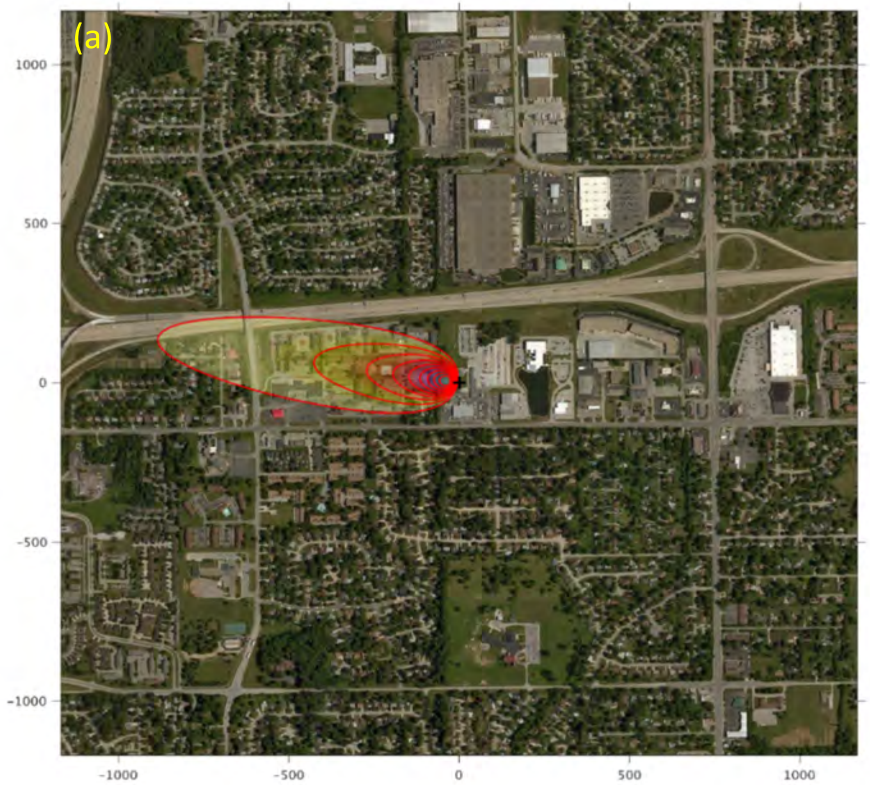
- No counter gradient flux (K > 0)
- No negative CO flux (delta CO > 0)
- K and F_{CO} are smaller than 3.5 σ

Downwind – upwind CO/CO2ff ratio from flasks defines R. Select R = 9 ppb / ppm.



Match every half-hourly flux footprint in space to the Hestia emissions map

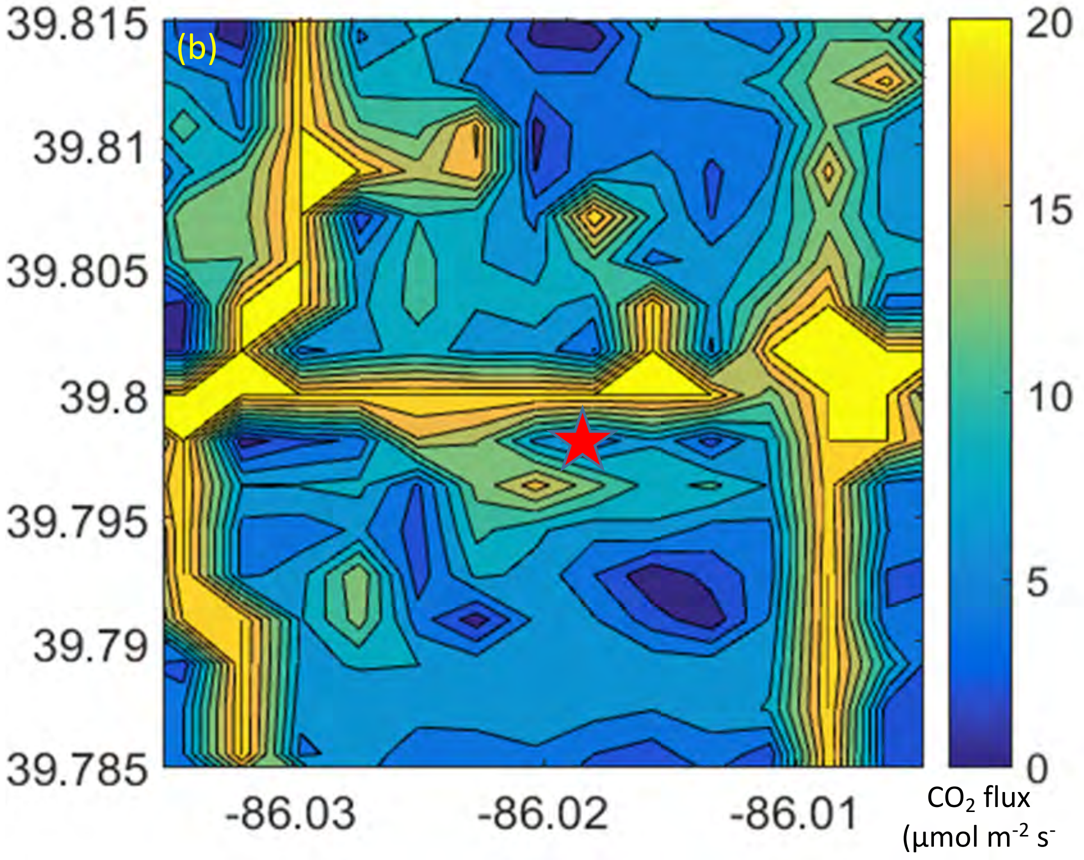
Flux footprint from one half-hourly data



Distance to the site (m)

- Flux footprint is related to instrument height, atmospheric stability and surface roughness.
- Tower measurements were used to calculate input parameters of flux footprint model.

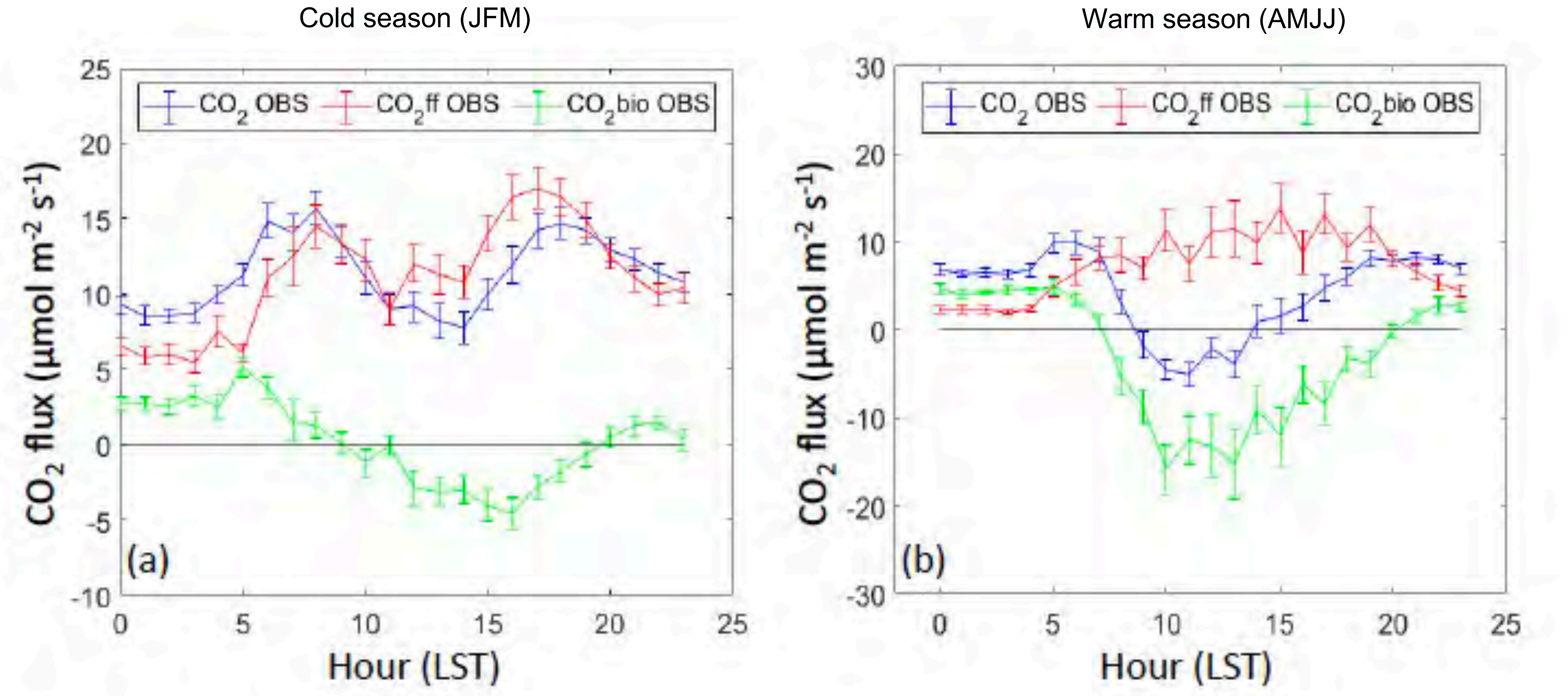
Annual mean of high-resolution (200m) Hestia emissions inventory



Note: emissions are limited to 20 µmol m^{-2} s^{-1} for visualization.

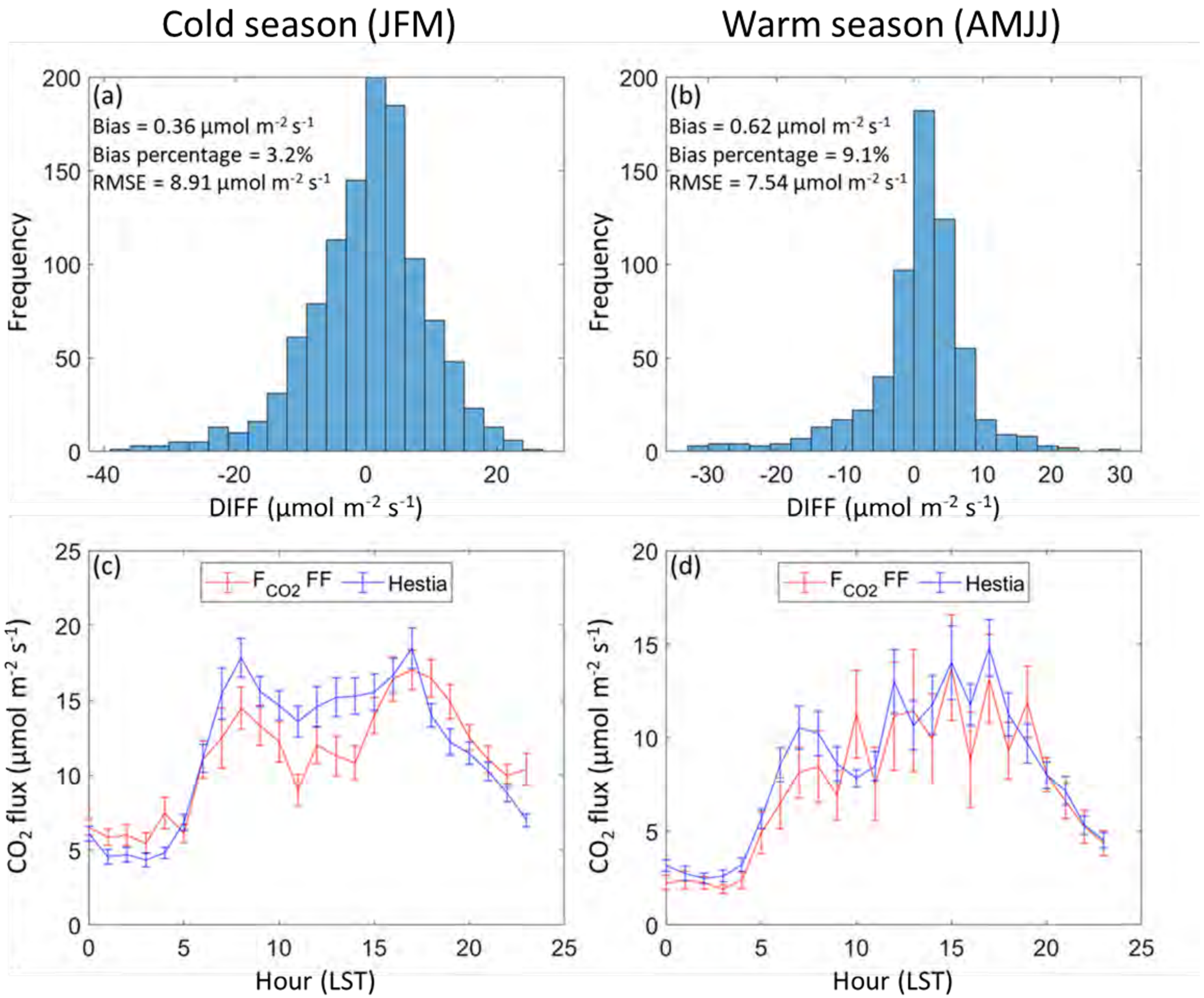
- Hestia has fine-scale spatial structure in urban CO_2 emissions, complementary to flux data.
- High emissions are correlated to the distribution of roads.

Flux decomposition yields fossil and bio CO_2 fluxes



Photosynthesis in the winter?

Hestia - Eddy Covariance bias and temporal pattern comparisons



Very small percentage bias (3%, 9%) in the seasonal averaged CO_2ff emissions.

Modest RMSE, probably dominated by sampling error from the eddy covariance methods.

Shockingly close agreement in the seasonal temporal pattern of CO_2ff emissions.

Wu et al, submitted

What are the implications of this comparison?

- For a first high-resolution (space and time) comparison between model and data, this is encouraging. Hestia takes a lot of work to create, but it appears to work very well.
- This flux decomposition approach also appears to work well.
- This lends confidence in our ability to deploy and use flux towers to construct additional detailed evaluation of our models of anthropogenic emissions.

- We don’t yet have a very high-resolution urban ecosystem model to test.

Can we apply this methodology to event detection and quantification?

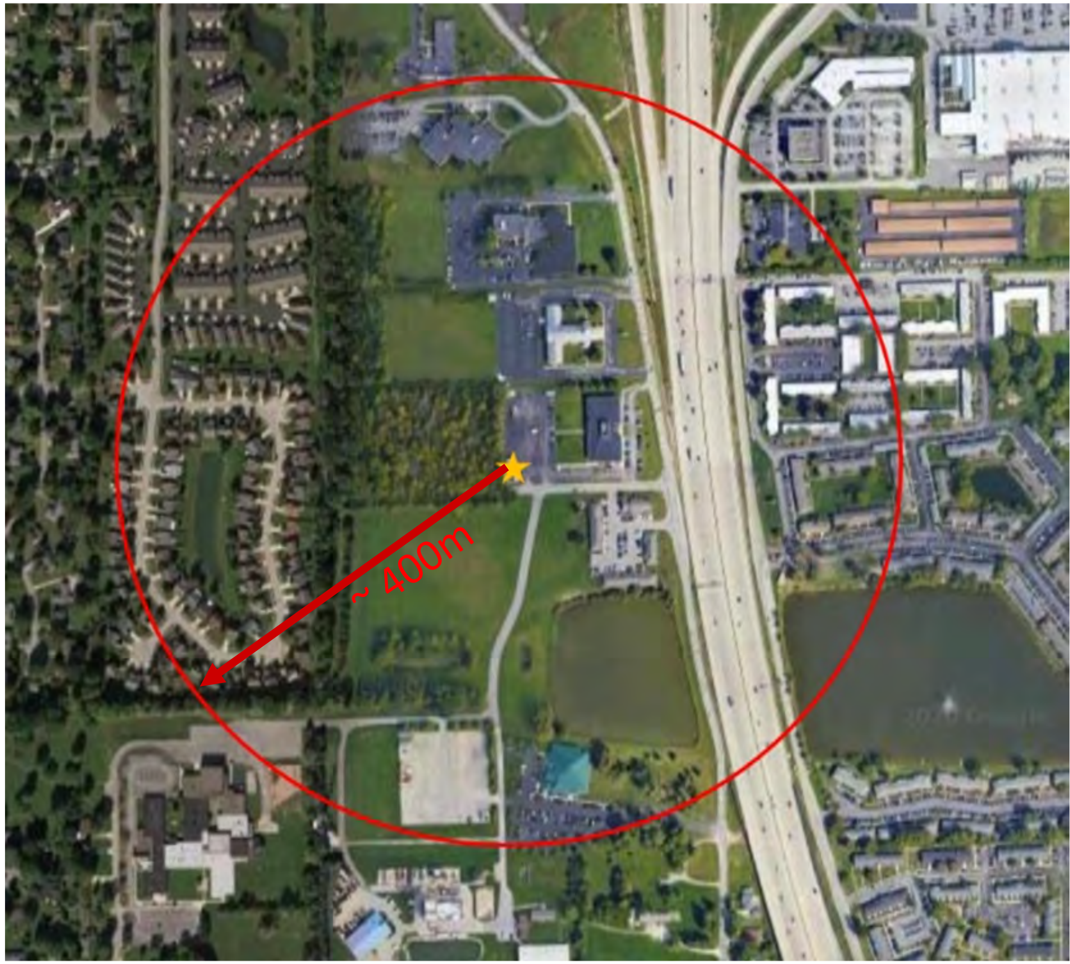
COVID lockdown test.

Vogel et al, in preparation

Though not its original mission, Tower 7 monitored emission changes due to COVID

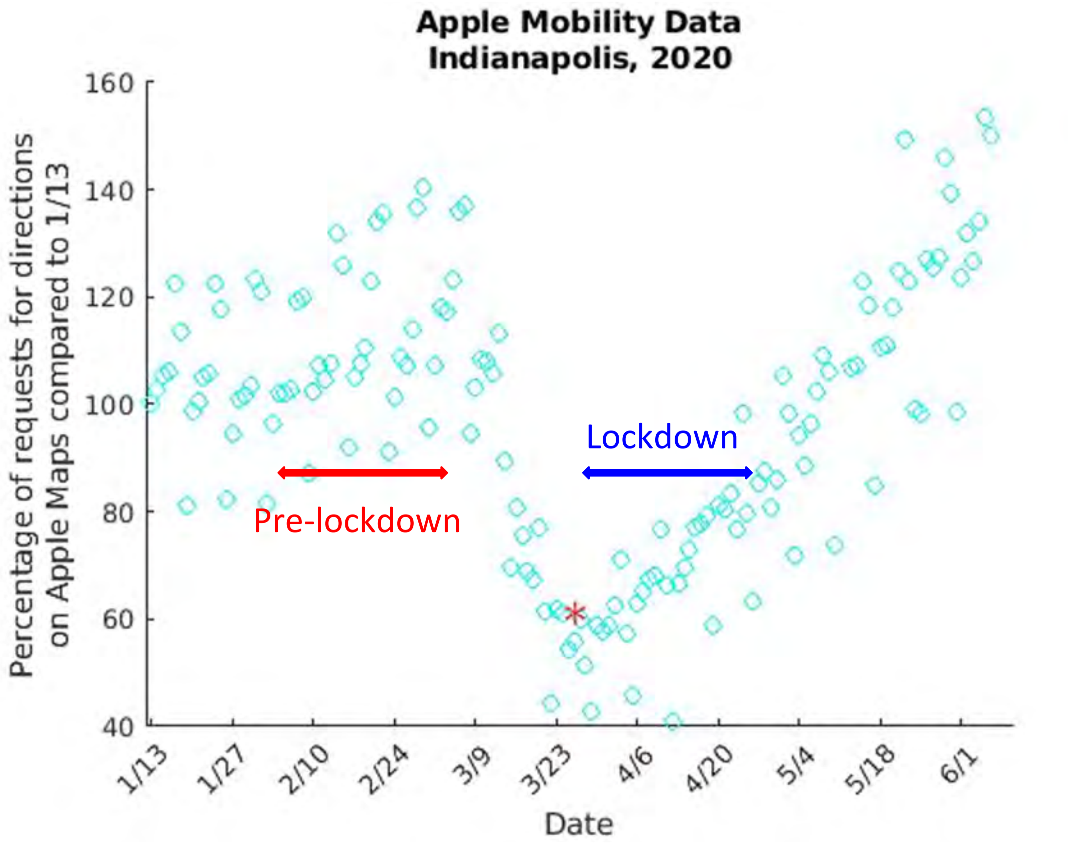
- We measure CO and CO_2 at 58 m and 21 m AGL via Picarro CRDS, and eddy covariance fluxes at 41 m AGL.
- Designed to monitor the urban forest to the west.

- Analysis uses CO_2 flux measurements from 41 m and mole fractional data from 21 and 58 m to estimate CO_2ff using Wu et al.'s method.
- Sample easterly winds to detect traffic emissions.
- CO/CO_2ff ratio is varied.



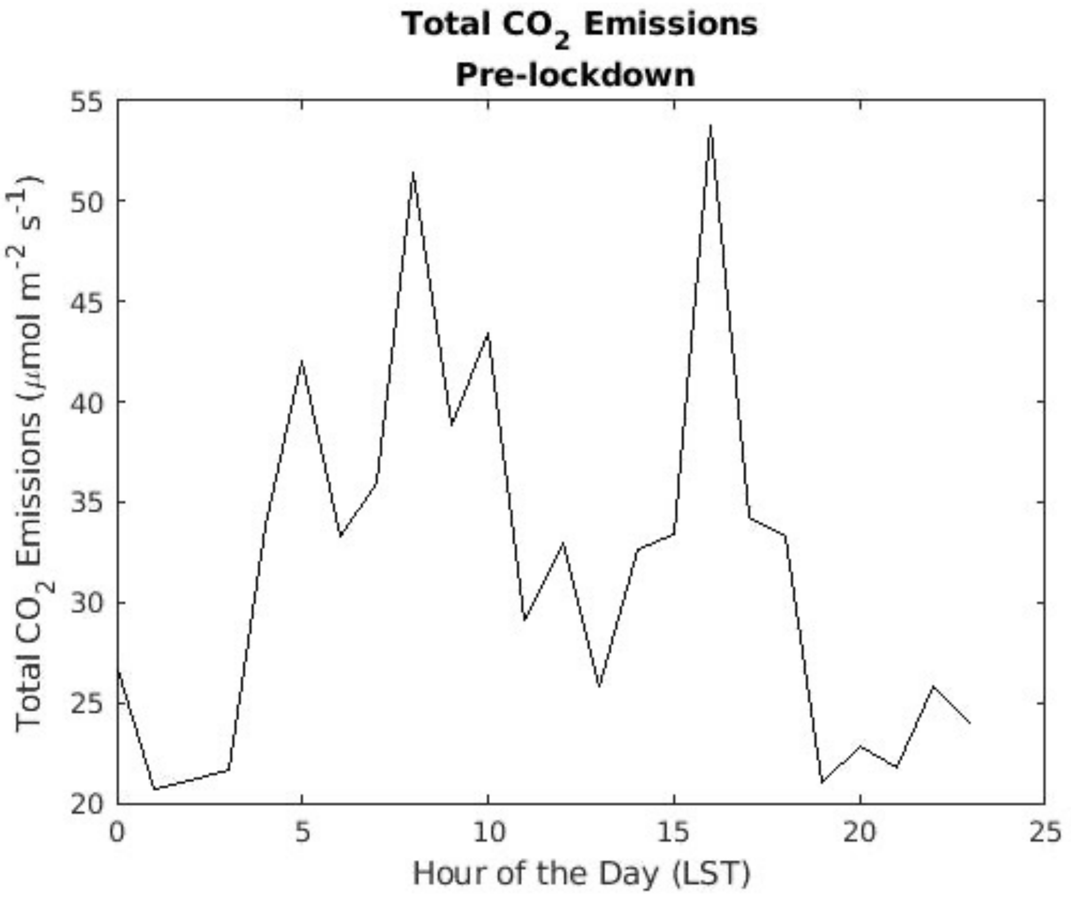
Location of tower 7, denoted by the yellow star.
Red circle delineates approximate footprint

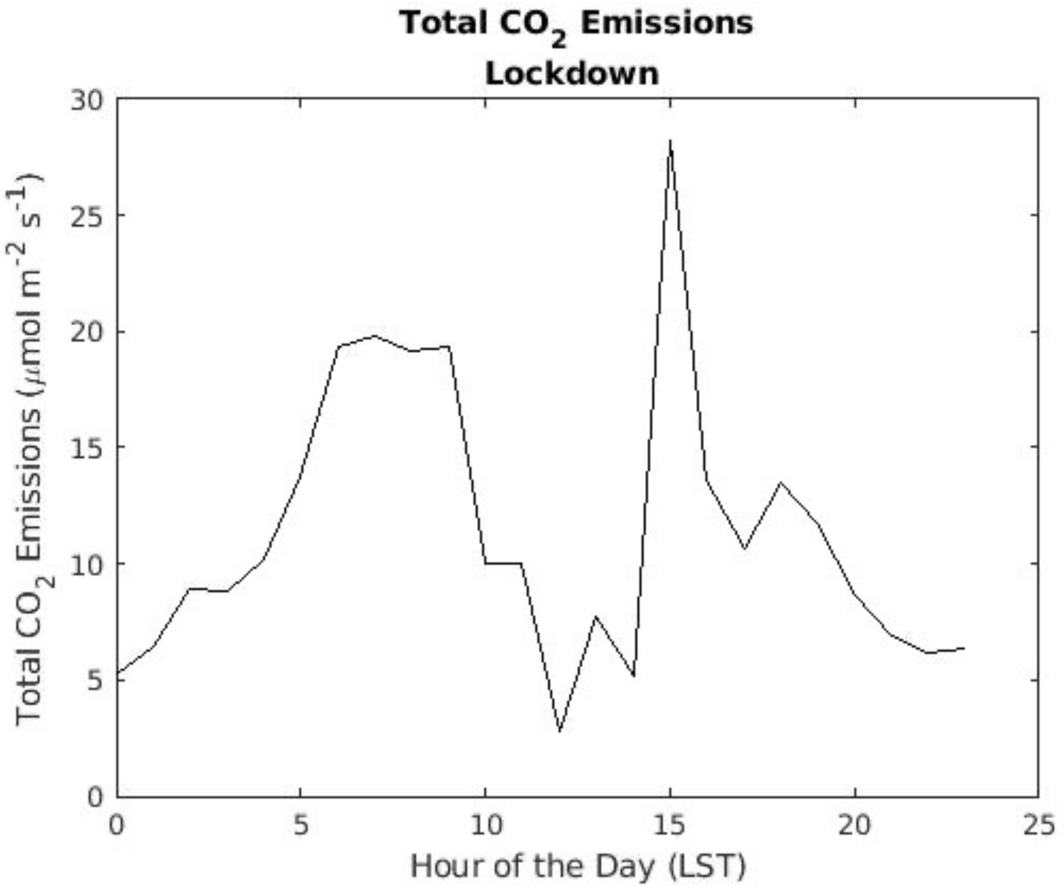
Apple mobility data used to identify lockdown period



Red asterisk marks March 24th, the day Indiana Governor Holcomb's statewide stay-at-home order took effect

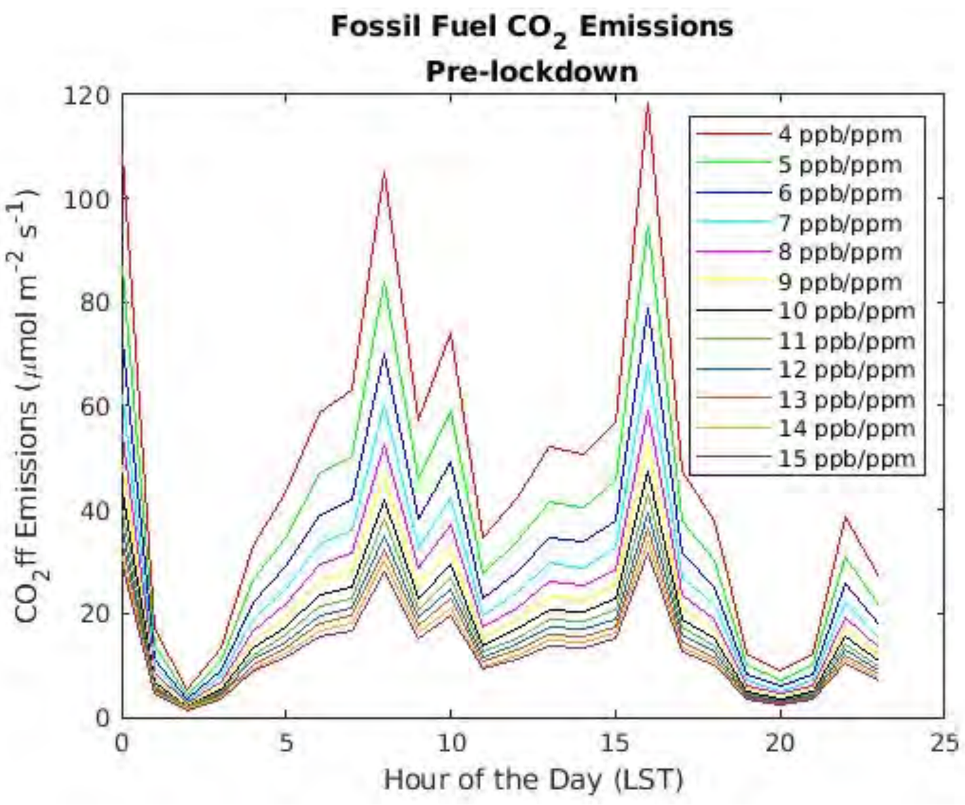
Total CO_2 flux from the highway shows a clear decrease

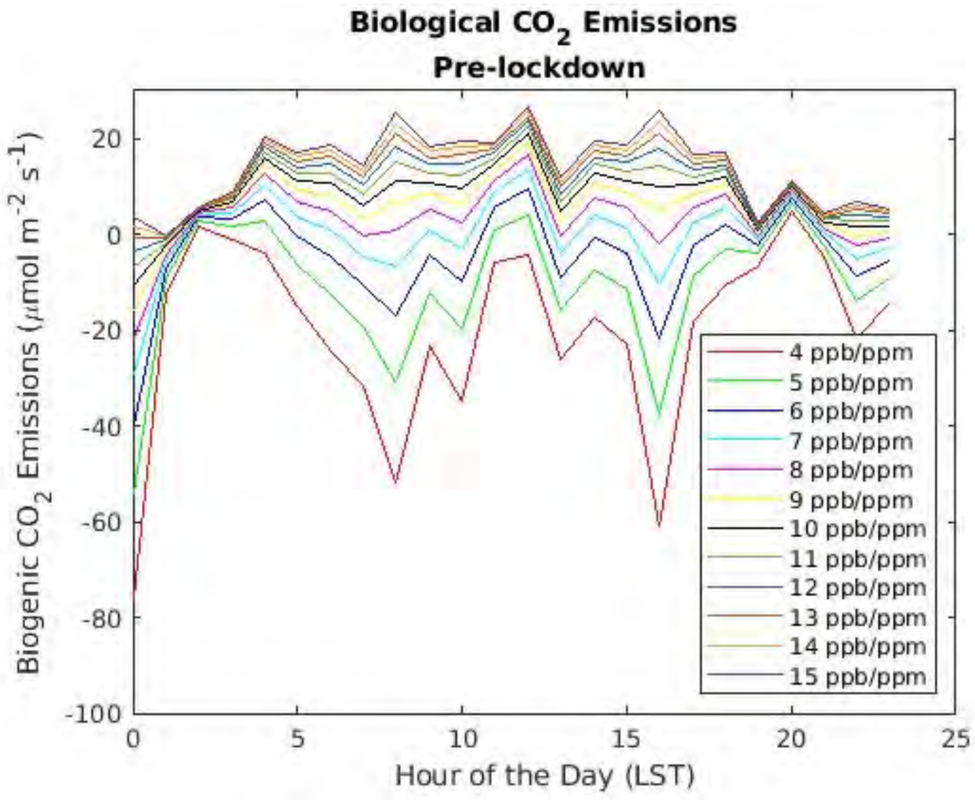




But this mixes biogenic and fossil emissions. Can we disaggregate?
What is the proper CO/CO_2ff ratio? If traffic changes, this ratio may change.

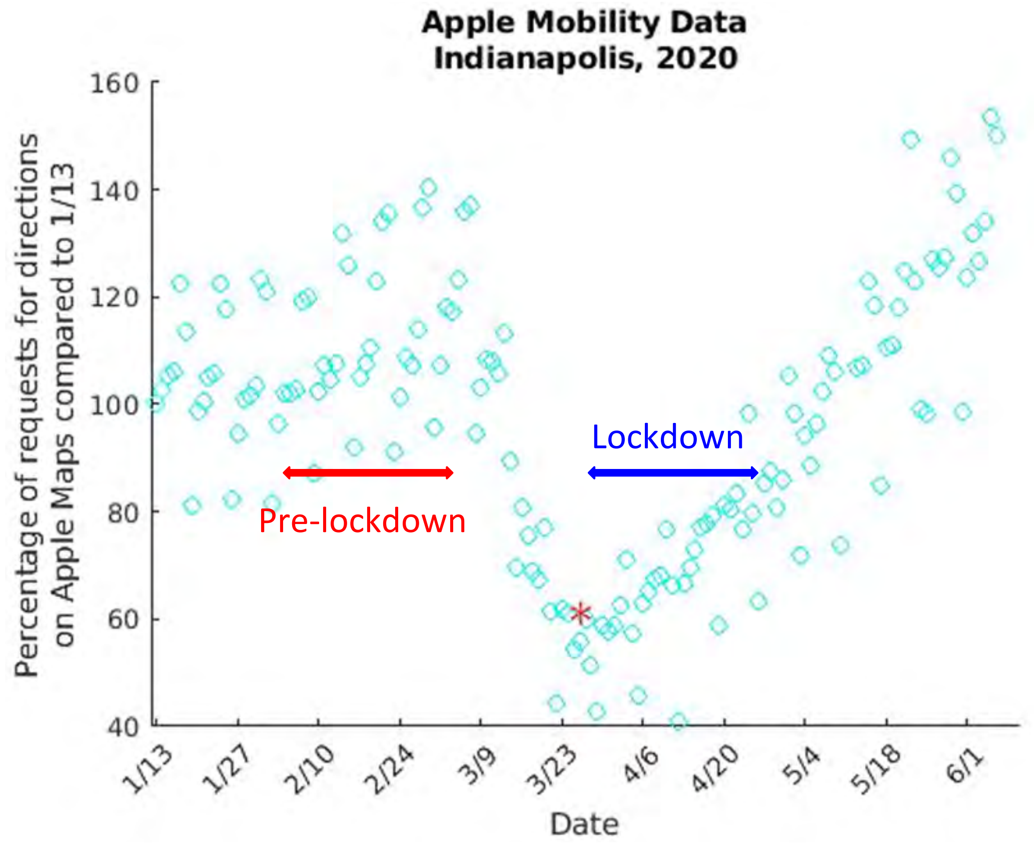
Search for plausible R value by requiring small BioCO_2 flux





No dedicated flask sampling of $^{14}CO_2$ on tower 7.
Winter conditions, highway-dominated footprint. Bio CO_2 fluxes are likely to be very small.
R value of 7-8 appears to be the most appropriate.
Roughly consistent with flask sampling that suggests city-wide R values of about 8 ppb/ppm (Turnbull et al., 2015)

There is a clear drop in CO_2ff emissions during lockdown



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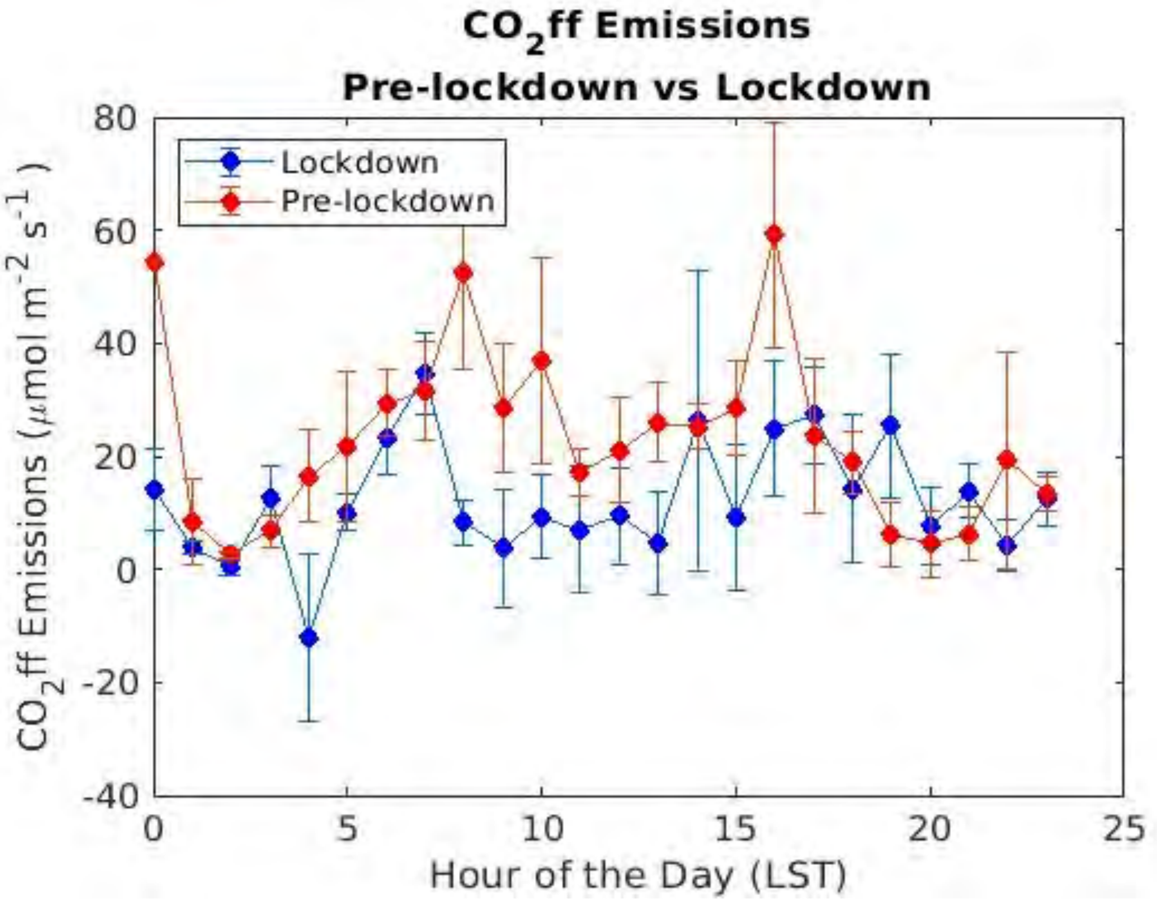
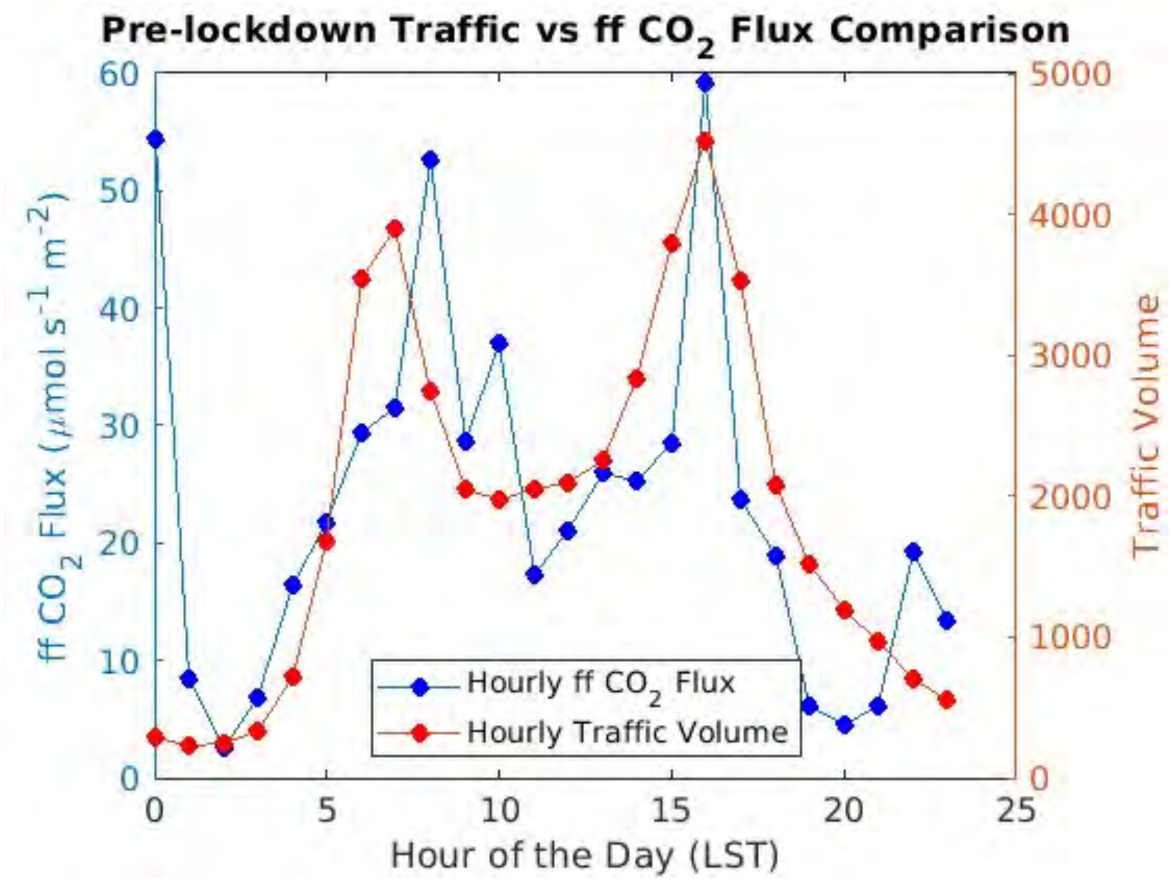
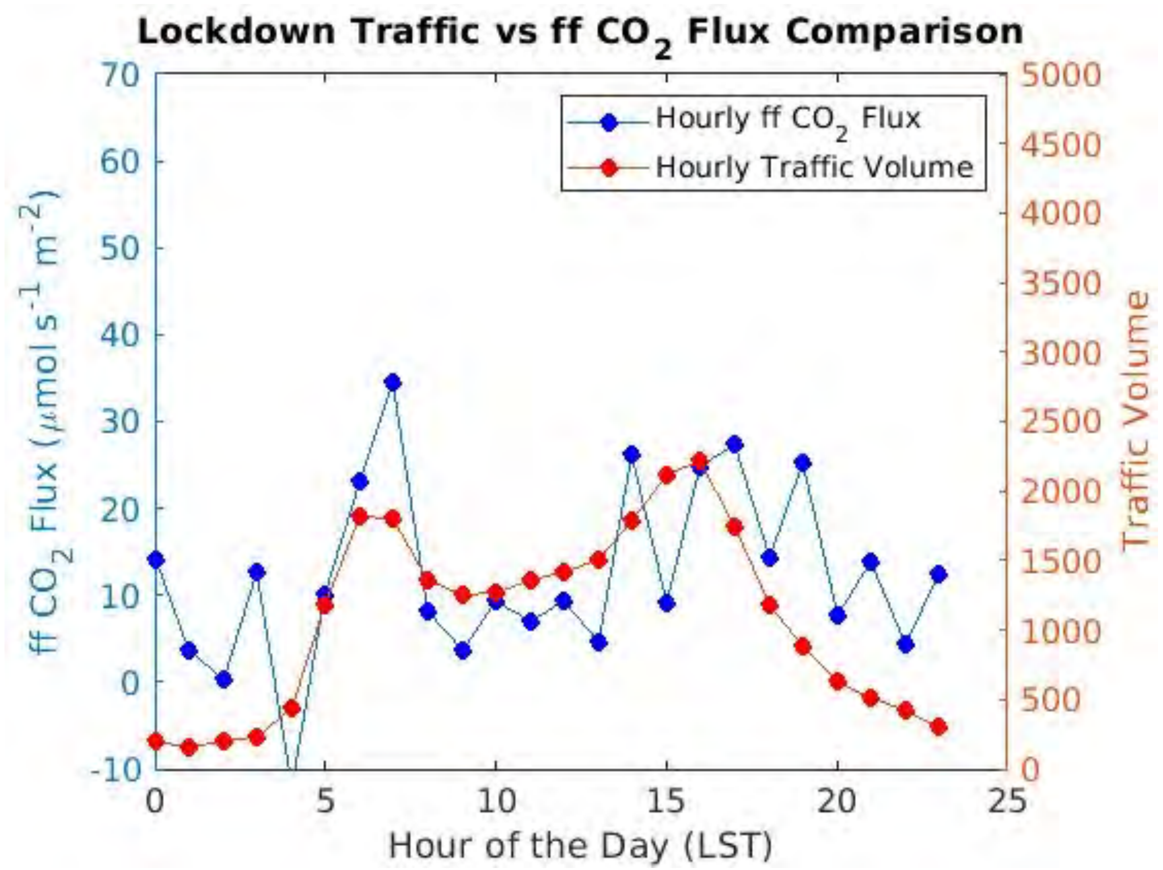


Error bars represent standard error derived from the hourly emissions being averaged.

The strong correlation between CO_2ff emissions and traffic becomes weaker during the lockdown





Traffic data from I-74, courtesy of the Indiana Department of Transportation (INDOT)

Implications

- Clear demonstration of the ability of an urban flux tower to track near-real-time changes in urban metabolism.

  (hopefully the next changes will be emissions mitigation efforts, not pandemics)
- Tracking events is a challenge for inventories...assembling data inputs can be time consuming and high temporal data may not be available.
- Atmospheric inversions can “see” these events as well but struggle to be highly resolved in space.
- Methods are complementary.

PennState

NIST

Next: Watching the grass grow...

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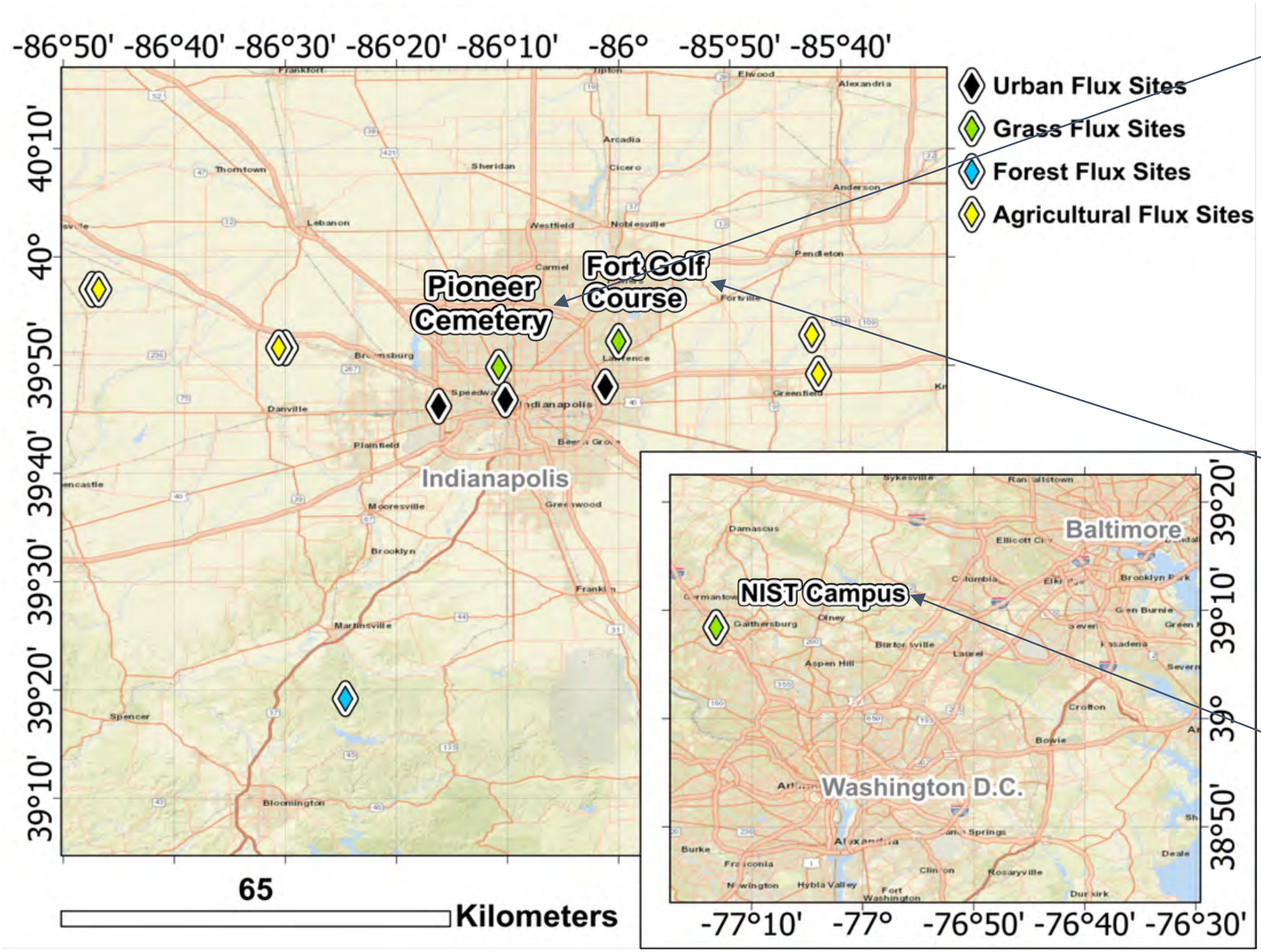
- We can use urban eddy covariance to evaluate the momentum and buoyancy fluxes driving urban ABL simulations (Sarmiento et al., 2017).

INFLUX + NIST grass flux tower sites



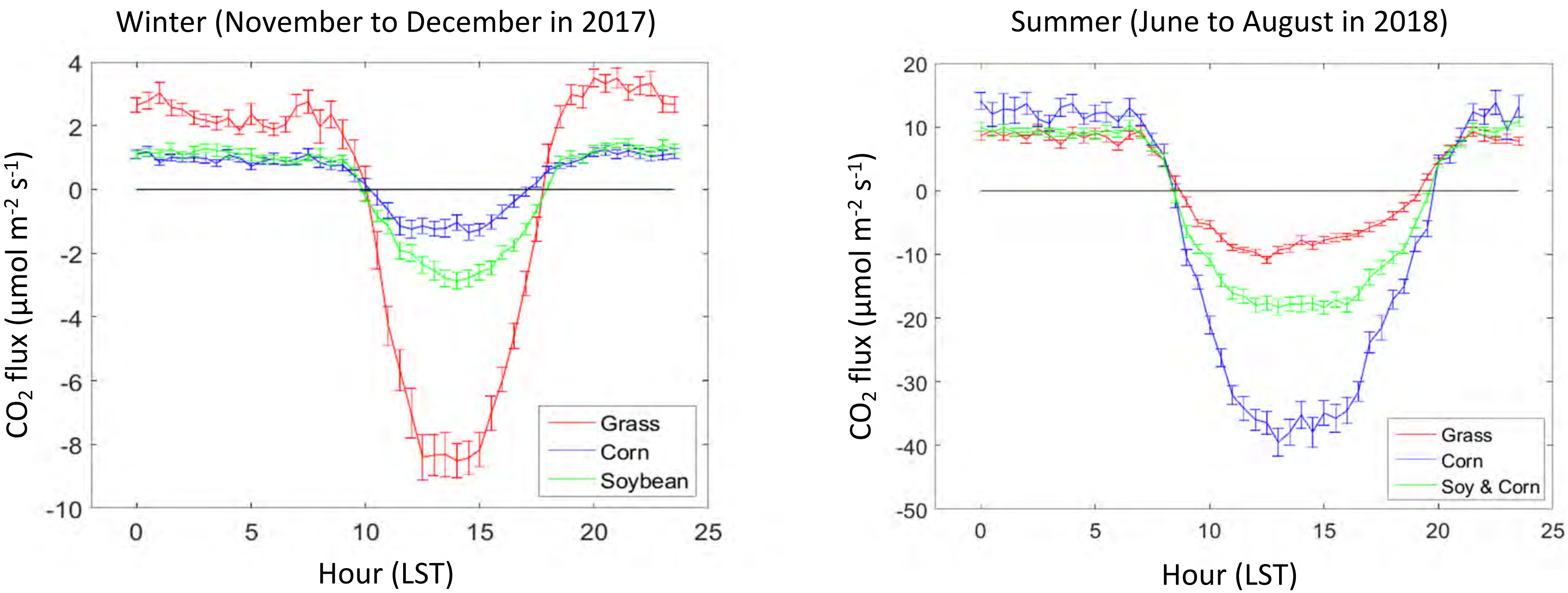
Three flux towers deployed over urban turf grass sites.

Small (~3 m) towers with small flux footprints.

Typical flux tower instrumentation.

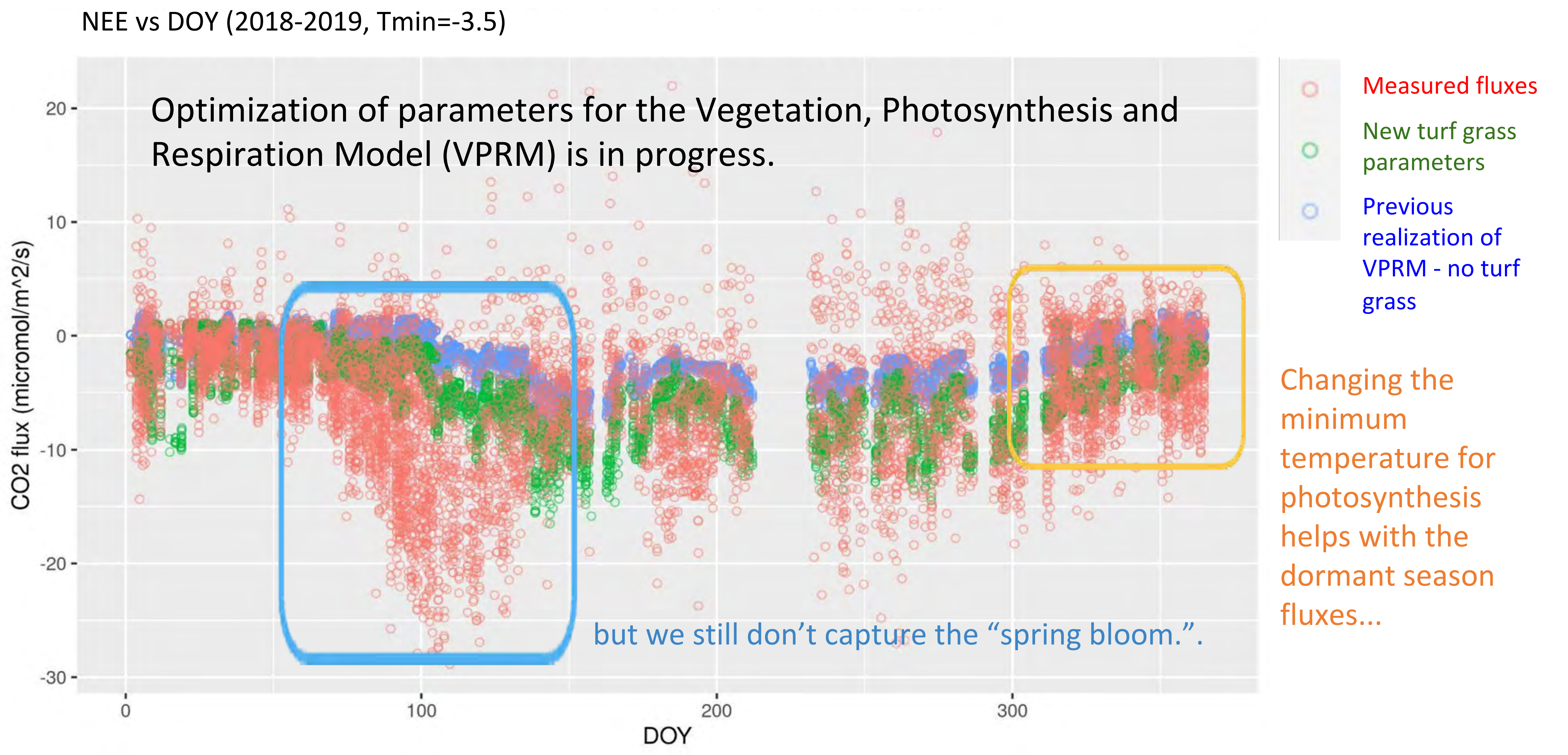
Two relatively unmanaged sites and one heavily managed site.

Turf grass is very active in the dormant season!



- Turf grass within the city shows large daytime fluxes (-8 µmol m^{-2} s^{-1}) in the dormant season.
- This daytime flux magnitude is comparable to fossil fuel emissions.
- First assumptions have been to ignore biology for dormant season atmospheric inversions.
- Current ecosystem model parameters aren't adapted to turf grass.

New parameter sets are needed for turf grass



Finally: Watching the corn grow…

Why? Isn't this a talk about using flux towers to study urban GHG fluxes?

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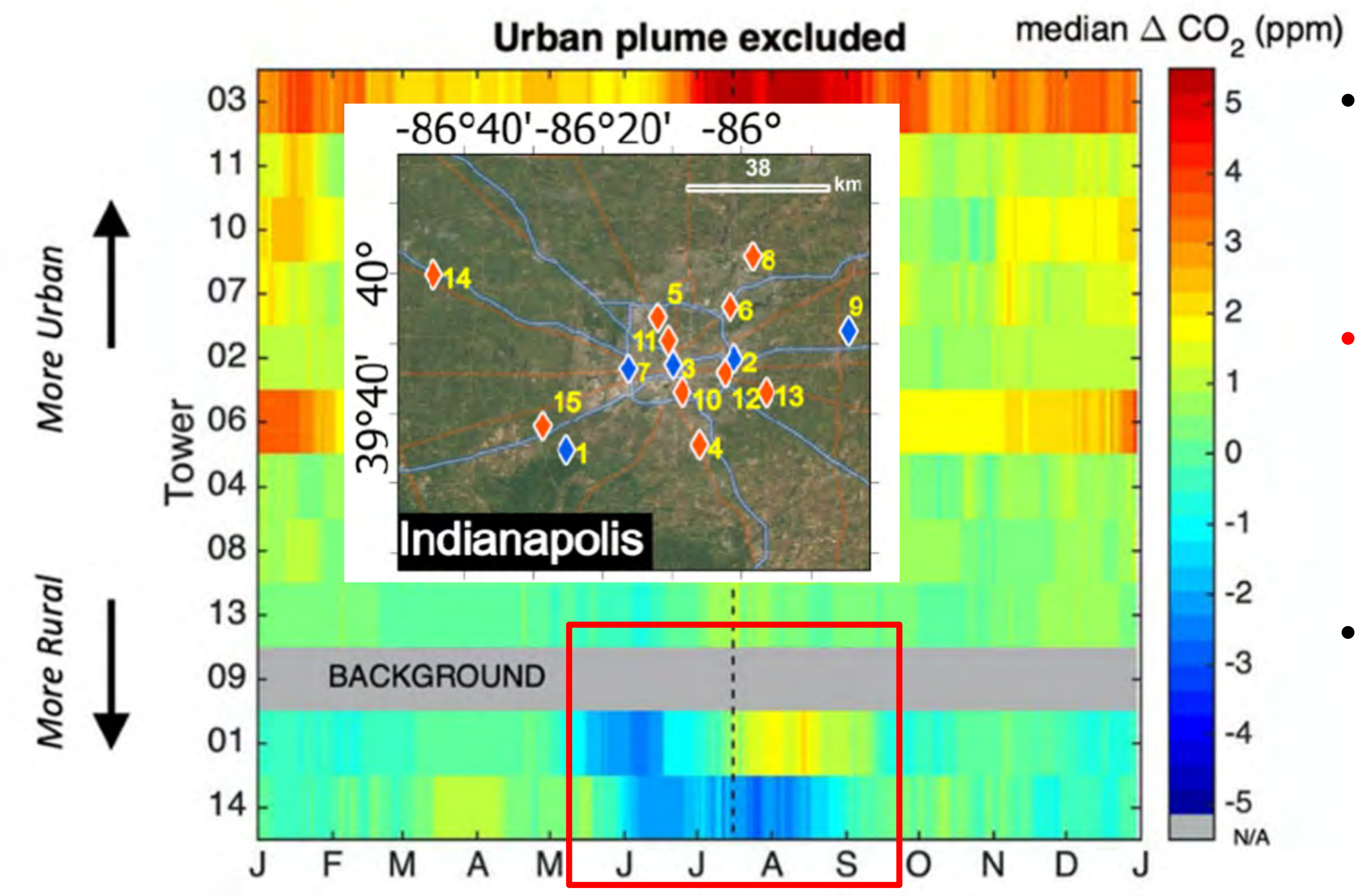
Why do agricultural fluxes matter when studying urban anthropogenic GHG emissions?



- We need to measure how the city adds GHGs to the local atmosphere. So, we need to quantify the regional CO_2 background.
- Growing season differences among "background" mole fraction observations can be the same order of magnitude as urban GHG enhancements.
- We need regional flux tower data to create a solid understanding of the variations in the rural CO_2 background.

Inset shows mole fraction towers. 01, 09 and 14 are "background" towers.

Miles et al., (2021)

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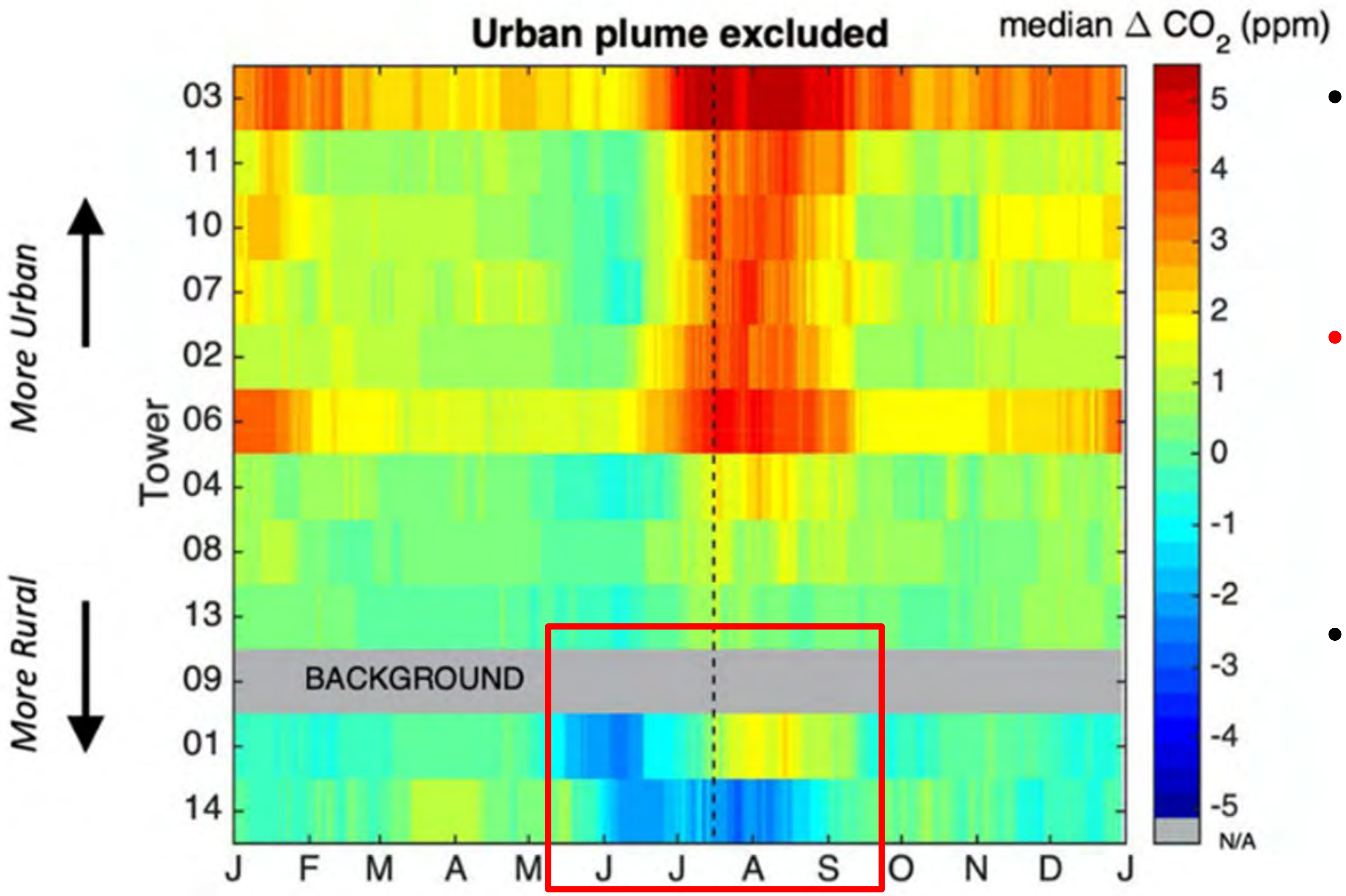

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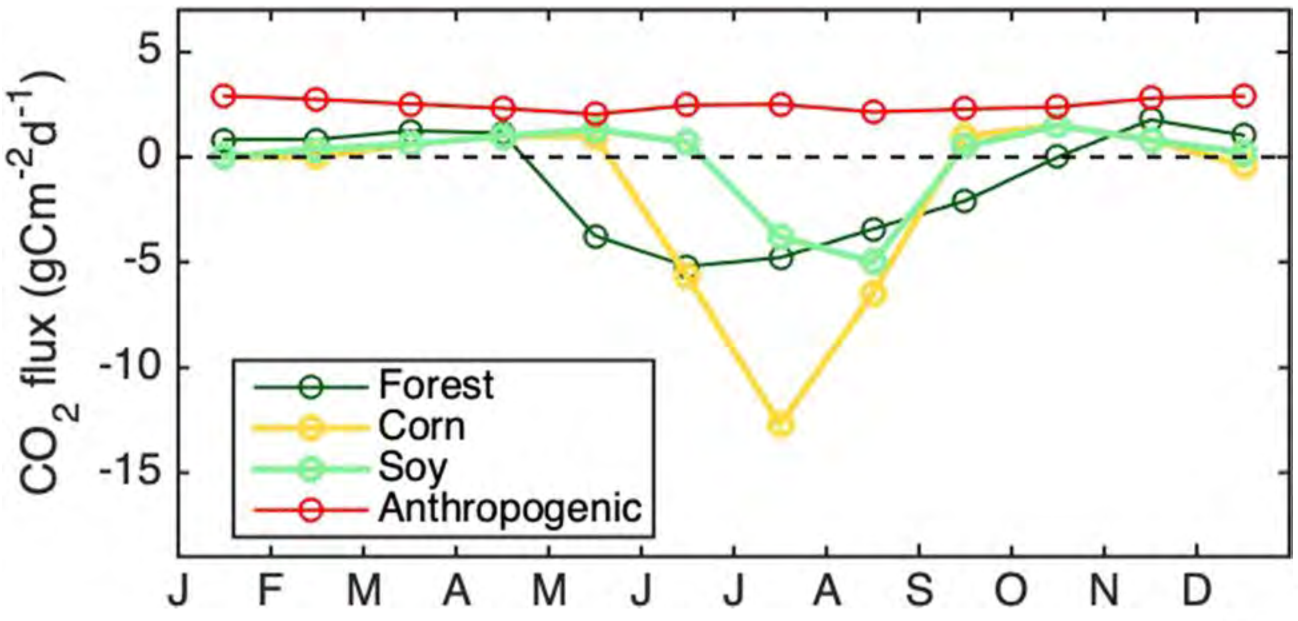
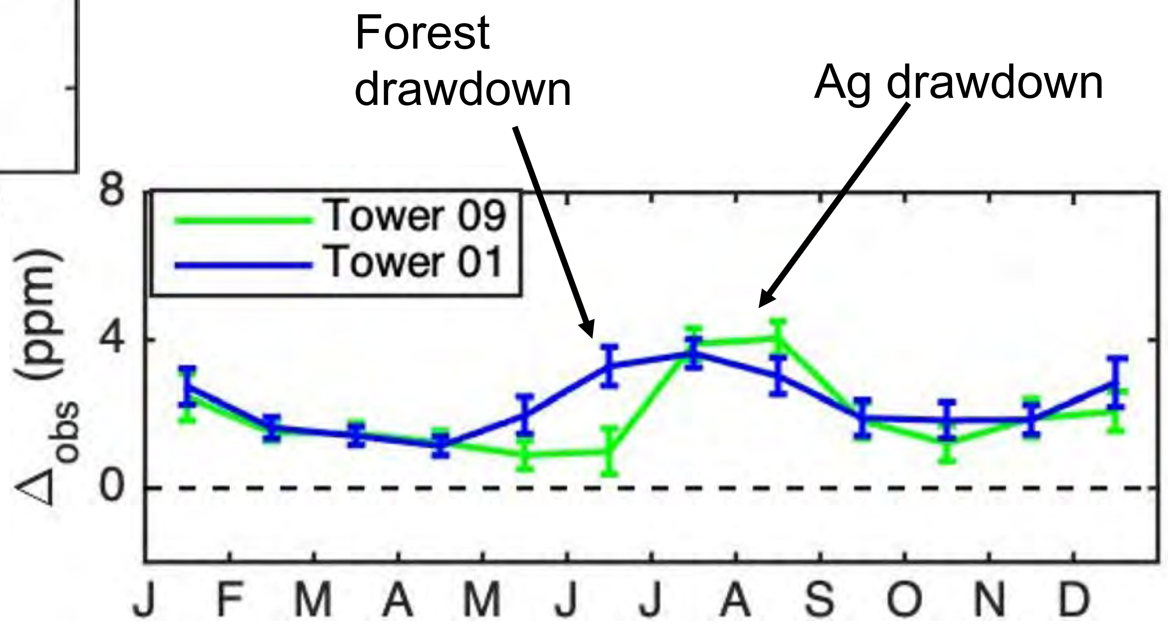
Indianapolis – Forest vs. Agricultural flux seasonality and amplitudes complicate the urban CO_2 background.



Morgan Monroe State Forest:
5-year mean: Novick et al. (2015)
Bondville Ameriflux towers:
3-year mean: Hollinger et al. (2005)
Hestia urban mean for anthro fluxes.



Miles et al, 2021

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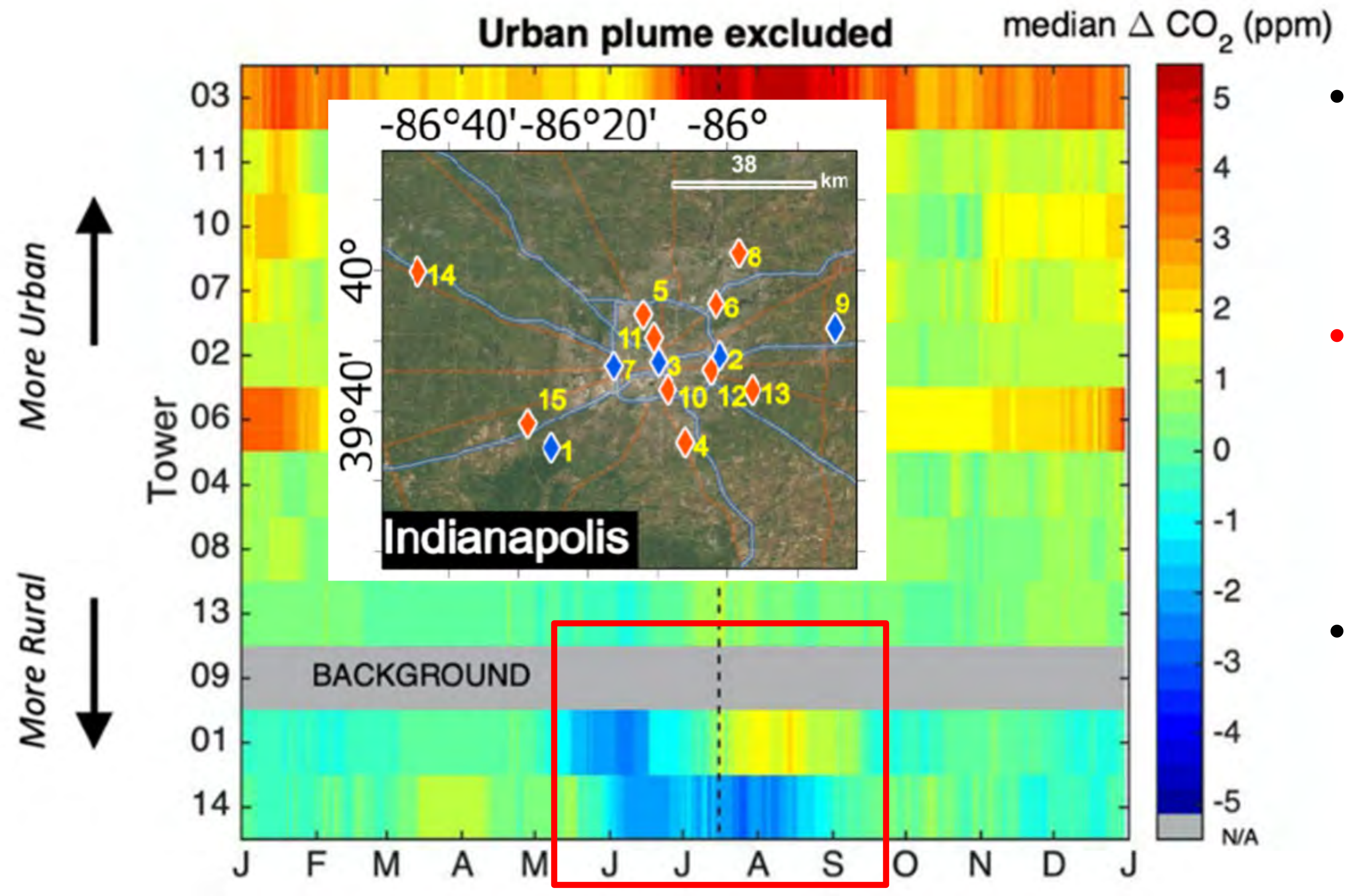

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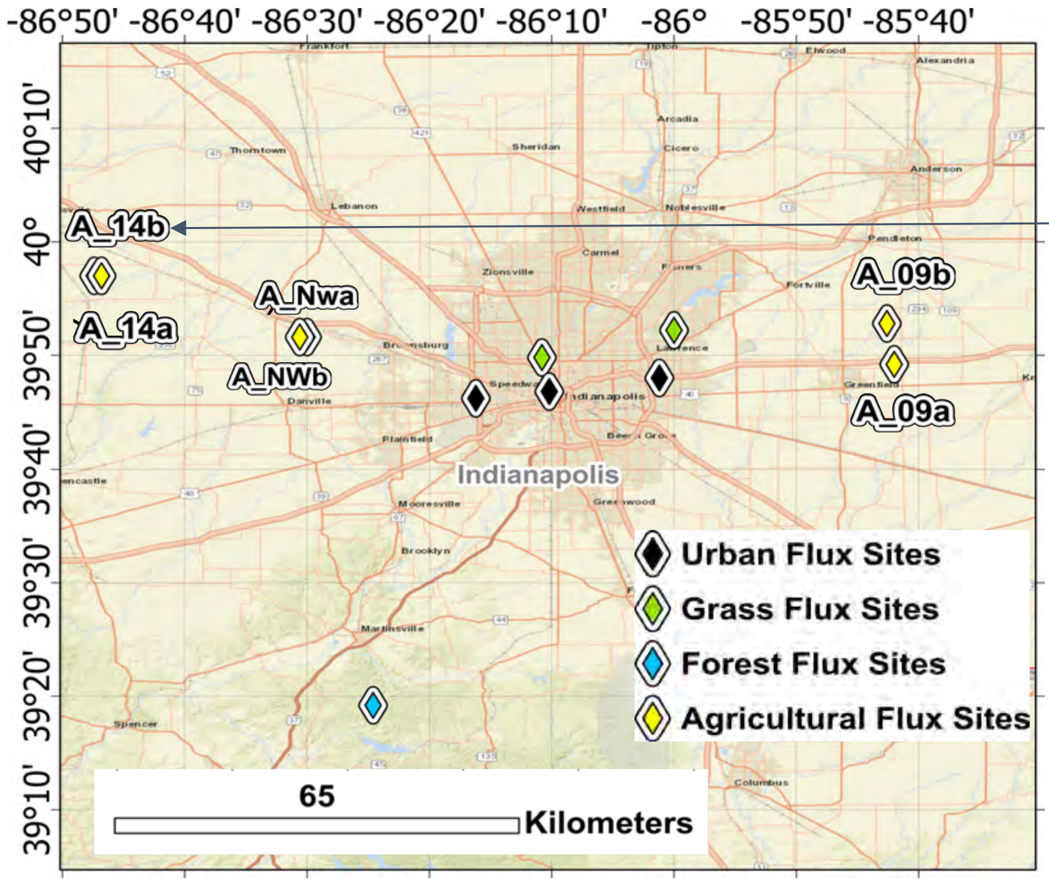
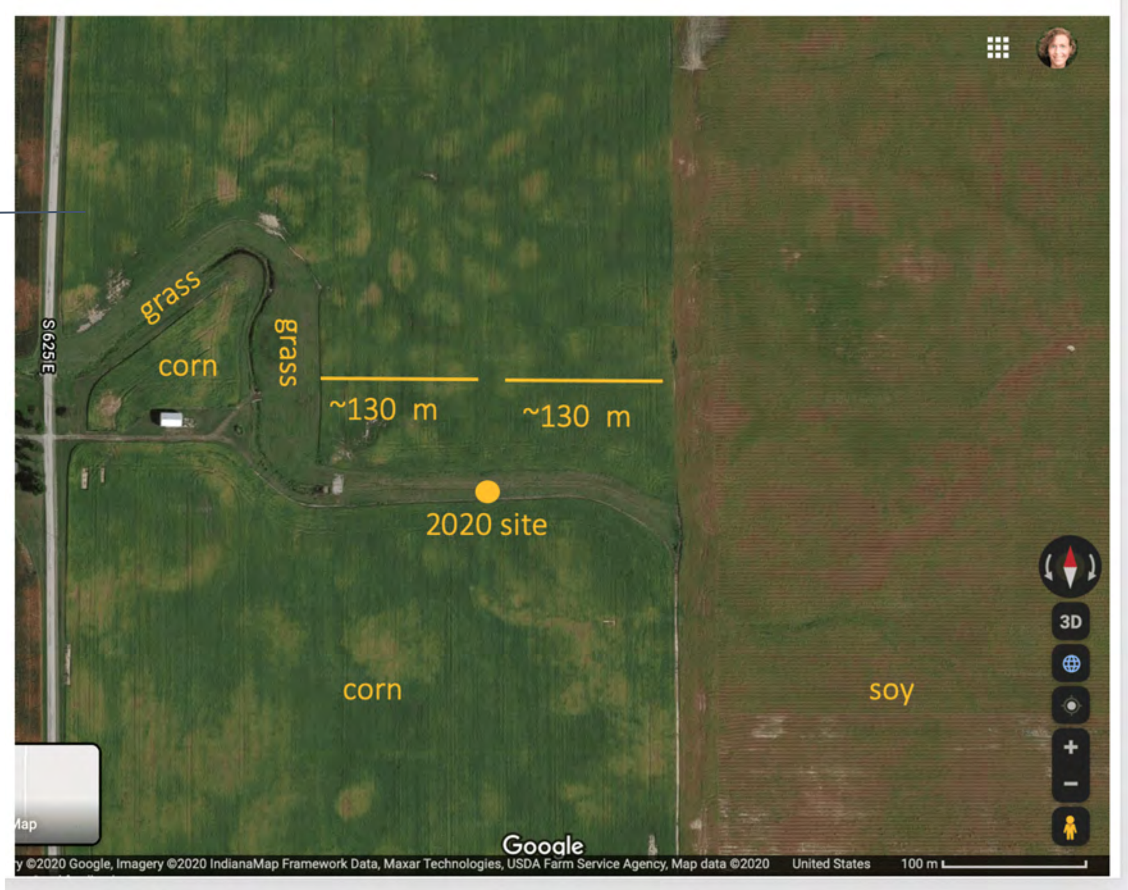
INFLUX agricultural flux towers: Understanding the rural background so that we can better understand the city.





- Multiple corn and soybean flux towers have been deployed and moved from site to site to study regional variations in fluxes.
- Corn productivity varies from west to east. Soy / corn density varies from west to east. Either / both could contribute to the complex background conditions we have observed.

Testing is underway

Vegetation Photosynthesis Respiration Model VPRM runs for a 300 x 300 km^2 grid around Indianapolis

Compare VPRM CO_2 flux outputs to agricultural eddy covariance measurements

- Does VPRM represent flux measurements? (If no, optimize)

Convolve VPRM CO_2 flux outputs with CO_2 concentration tower influence functions

- Does VPRM explain the background mole fraction differences observed in Miles et al., (2021)?

Use VPRM to represent rural background conditions for Urban Inversions

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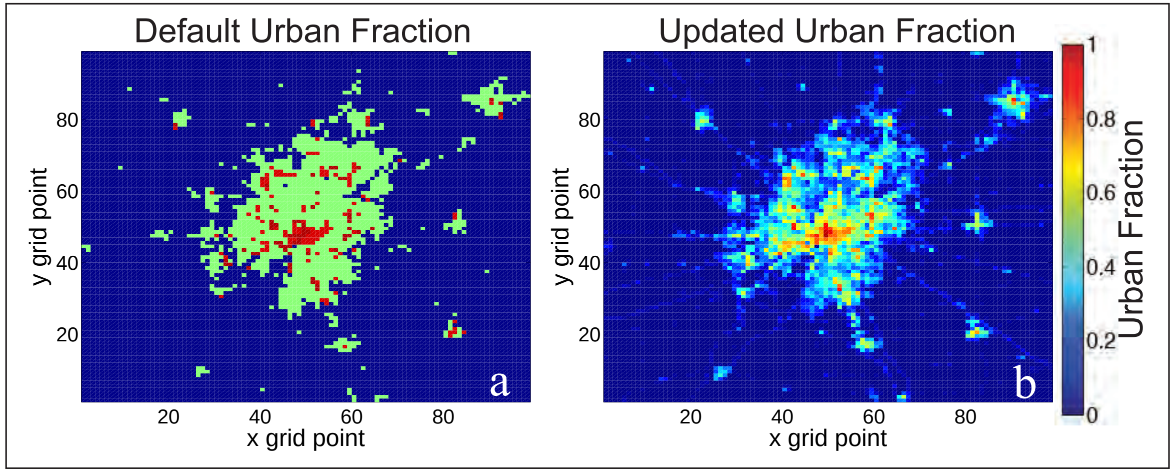
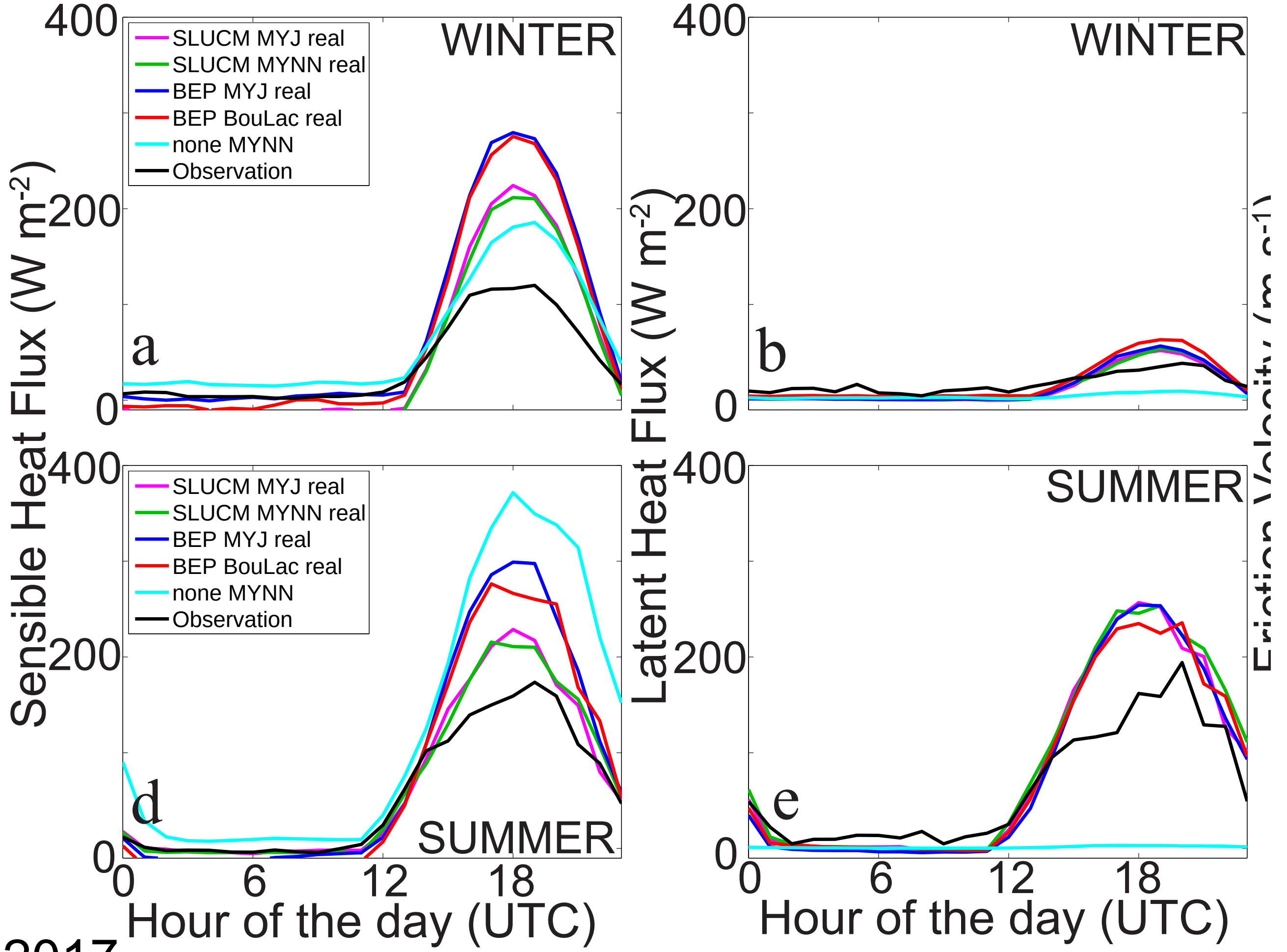
Urban land cover in WRF leads to systematic biases in surface fluxes



WRF makes Indy a parking lot by default. Urban sensible heat fluxes are greatly overestimated.

Tiling the land surface improves the surface energy balance.

Comprehensive ABL depth evaluation (rural and urban) is underway.



Sarmiento et al, Elementa, 2017

Conclusions

- Urban flux towers can be used, *with appropriate data decomposition methods and tower placement strategies*, for direct, quantitative tests of urban anthropogenic and biogenic flux models.
- This work complements atmospheric inversions.
- These measurements also help us to improve our models of surface energy and momentum fluxes needed for atmospheric transport models.
- This is exactly why we make our “rural system” eddy covariance measurements!
- We need:
  - More suitably instrumented and located flux tower sites.
  - Advances in flux footprint models and tracer ratio methods.
  - High resolution anthropogenic and biogenic flux models suitable for urban systems.
  - Clear linkages to urban GHG mole fraction networks and urban inversion testbeds. Don’t keep these systems separate!

References

Gurney, K.R., et al. (2012). Quantification of Fossil Fuel CO_2 Emissions on the Building/Street Scale for a Large U.S. City. *Environ. Sci. Technol.*, *46*, 21, 12194–12202. https://doi.org/10.1021/es3011282.

Heimberger, Alexie M. F., Paul B. Shepson, Brian H. Stirm, Chloe Susdorf, Jocelyn Turnbull, Maria O. L. Cambaliza, Olivia E. Salmon, Anna-Elodie M. Kerlo, Tegan N. Lavoie, Rebecca M. Harvey, Kenneth J. Davis, Thomas Lauvaux, Anna Karion, Colm Sweeney, W. Allen Brewer, R. Michael Hardesty, Kevin R. Gurney, James Whetstone, 2017. Precision Assessment for the Aircraft Mass Balance Method for Measurement of Urban Greenhouse Gas Emission Rates. *Elem Sci Anth*. 2017;5:26. DOI: http://doi.org/10.1525/elementa.134

Lauvaux, T., K.R. Gurney, N.L. Miles, K.J. Davis, S.J. Richardson, A. Deng, B.J. Nathan, T. Oda, J.A.Wang, L.R. Hutyra, and J.C.Turnbull, 2020. Policy-relevant assessment of urban greenhouse gas emissions, Environ Sci Tech. 54, 16, 10237–10245, doi:10.1021/acs.est.0c00343.

Miles, Natasha L., Kenneth J. Davis, Scott J. Richardson, Thomas Lauvaux, Douglas K. Martins, A. J. Deng, Nikolay Balashov, Kevin R. Gurney, Jianming Liang, Geoff Roest, Jonathan A. Wang, 2021: The influence of near-field fluxes on seasonal carbon dioxide enhancements: results from the Indianapolis Flux Experiment (INFLUX). Carbon Balance and Management, 16:4, https://doi.org/10.1186/s13021-020-00166-z

Miles, Natasha L., Scott J. Richardson, Thomas Lauvaux, Kenneth J. Davis, Aijun Deng, Jocelyn Turnbull, Anna Karion, Colm Sweeney, Kevin R. Gurney, Risa Patarasuk, Igor Razlivanov, Maria O. Cambaliza and Paul B. Shepson, 2017. Quantification of urban atmospheric boundary layer greenhouse gas dry mole fraction enhancements: Results from the Indianapolis Flux Experiment (INFLUX), *Elem Sci Anth*. 2017;5:27. DOI: http://doi.org/10.1525/elementa.127

Sarmiento, Daniel P., Kenneth J. Davis, Aijun Deng, Thomas Lauvaux, Alan Brewer, Michael Hardesty, 2017. A comprehensive assessment of land surface-atmosphere interactions in a WRF/Urban modeling system for Indianapolis, IN, *Elem Sci Anth*: 2017;5:23. DOI: http://doi.org/10.1525/elementa.132

Turnbull, Jocelyn C., Anna Karion, Kenneth J. Davis, Thomas Lauvaux, Natasha L. Miles, Scott J. Richardson, Colm Sweeney, Kathryn McKain, Scott J. Lehman, Kevin R. Gurney, Risa Patarasuk, Jianming Liang, Paul B. Shepson, Alexie Heimburger, Rebecca Harvey, and James Whetstone, 2019. Synthesis of Urban CO2 Emission Estimates from Multiple Methods from the Indianapolis Flux Project (INFLUX). Environmental Science & Technology **2019** *53* (1), 287-295, DOI:10.1021/acs.est.8b05552.

Wu, Kai, Thomas Lauvaux, Kenneth J. Davis, Aijun Deng, Israel Lopez Coto, Kevin R. Gurney and Risa Patarasuk, 2018. Joint inverse estimation of fossil fuel and biogenic CO2 fluxes in an urban environment: An observing system simulation experiment to assess the impact of multiple uncertainties. Elem Sci Anth. 2018;6(1):17. DOI: http://doi.org/10.1525/elementa.138