DC's tree canopy lowers urban air temperature, but the cooling magnitude depends on spatial context and time of day

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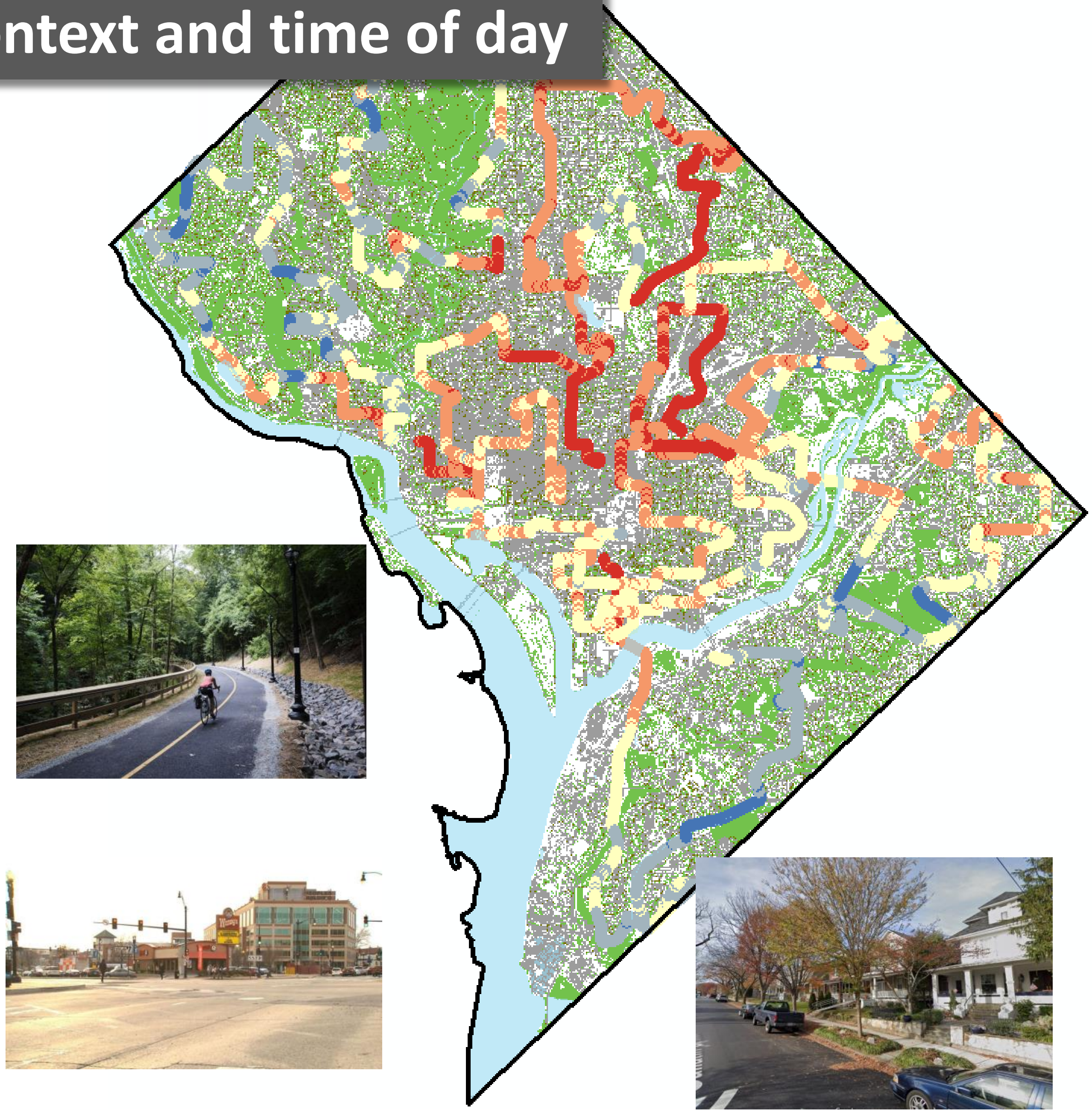
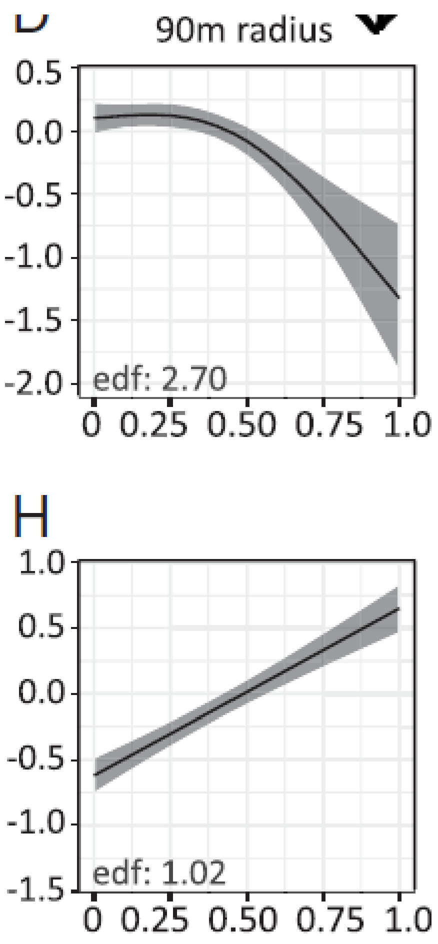
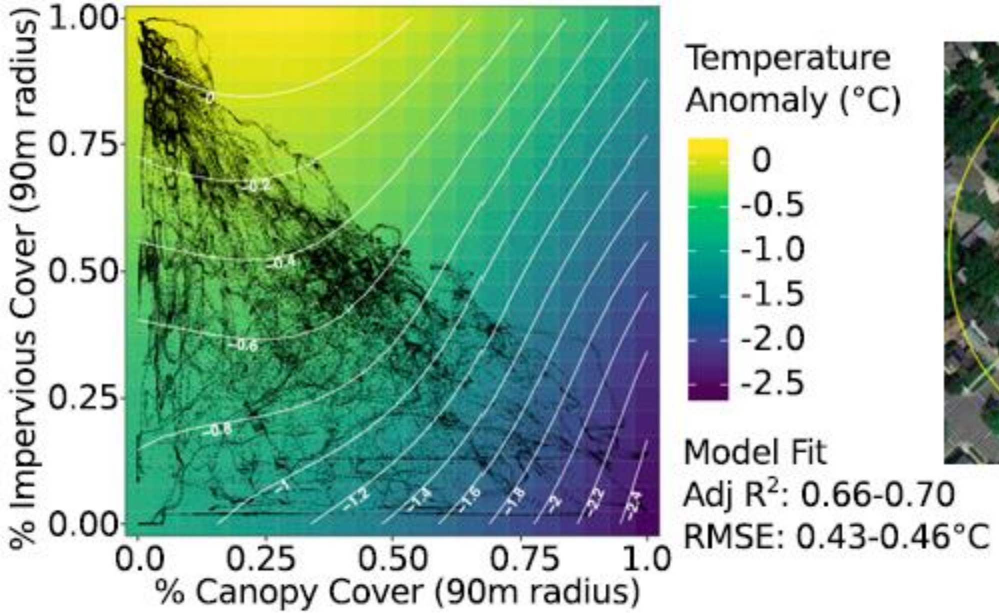


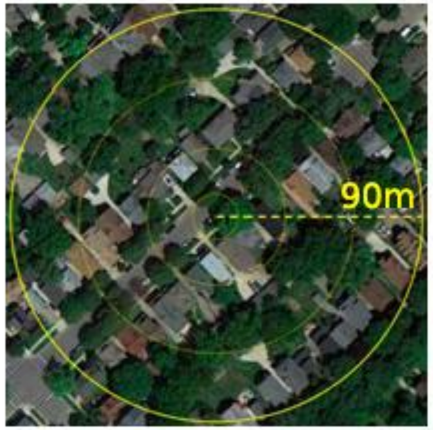
Motivation

- There may be a threshold effect whereby canopy cover fraction needs to be 0.4 or 0.5 to lead to substantial cooling (Ziter 2019; Jung 2020; Alavipanah 2015)
- With a single, “tree canopy” variable or in some cases just a “land cover greenness” variable, it is difficult to understand the drivers of this nonlinearity
- Canopy over unpaved surfaces has been shown to be a strong cooler (Shashua-Bar 2009) but there is limited observational, urban research corroborating this.

Nonlinear relationship between canopy cover fraction and cooling. Linear relationship between impervious surface and warming (Ziter 2019)







Interaction between canopy and impervious surface in the afternoon (Ziter 2019)

Motivation

- Tree canopy modulation of temperature by time of day, not well characterized
    - Tree canopy over impervious surface (“hard canopy”) may cool through shading or may warm through heat trapping (the latter particularly at night)
    - Canopy over unpaved surface (“soft canopy”) cools during the day but may: 1) continue cooling at night; 2) have minimal effect at night; 3) slightly warm at night.

- Tree canopy modulation of temperature can depend on the spatial configuration of the canopy and the spatial scale of measurement
    - Park Cool Island effect (but distance from park?)
    - Minimal examination of distributed soft canopy

Shandas et al., (2019) showing heat island development throughout the day in DC

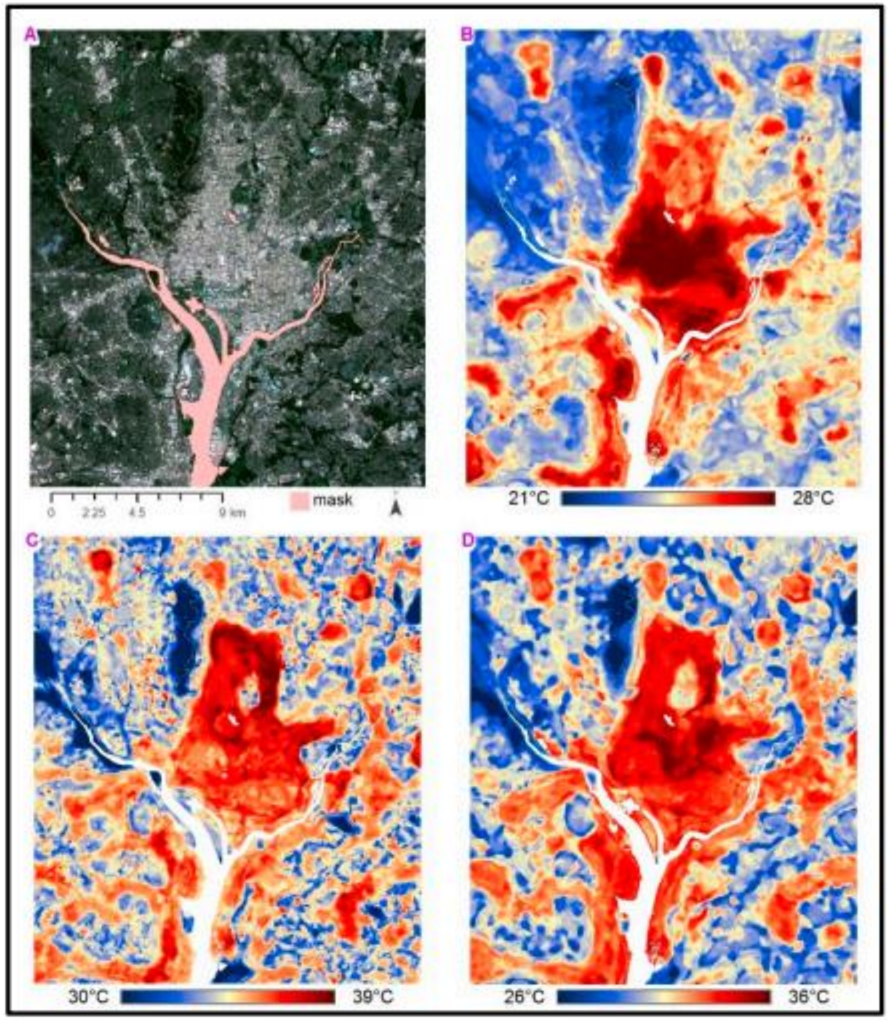


Figure 2. Washington, D.C. (**A**) aerial imagery with major waterbodies masked; (**B**) morning UHI; (**C**) afternoon UHI; (**D**) evening UHI.

Research Questions

1. How does tree canopy (broadly speaking) regulate air temperature in a large, humid-subtropical city?

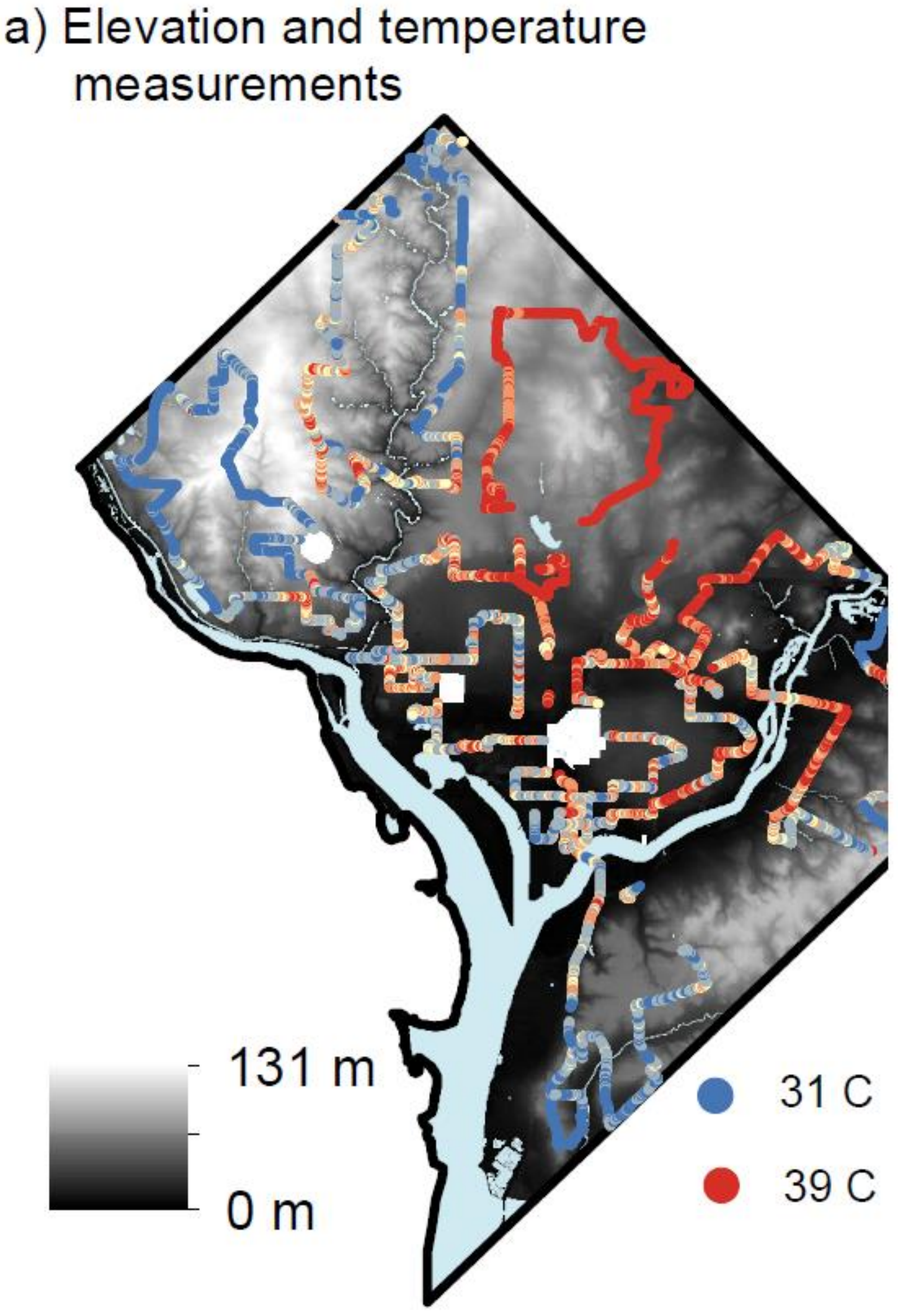
2. What are the relative contributions to temperature modification by hard canopy, soft canopy, and impervious surface cover?

3. Is it more effective to cool a city using large forest patches (i.e., parks) or evenly distributed canopy?

4. How does temperature modification by canopy (all the above-mentioned classes) change depending on time of day?

Methods: Temperature data collection

- **Temperature measurement** **(Shandas et al., 2019, Urban Climate)**
  - Single day campaign on hot day in 2018 (August 28)
  - 9 Car "transects" to maximize spatial coverage within a 1-hour sampling window
  - Collection times:
    - 5 am to 6 am (22 to 28 C)
    - 2 pm to 3 pm (30 to 38 C)
    - 6 pm to 7 pm (26 to 35 C)
  - Mobile temps converted to anomaly based on 4 downtown DC stations (WaPo, NoMA, West End, Dupont North)



Methods: Variables

The set of calculated variables.

Important to account for:

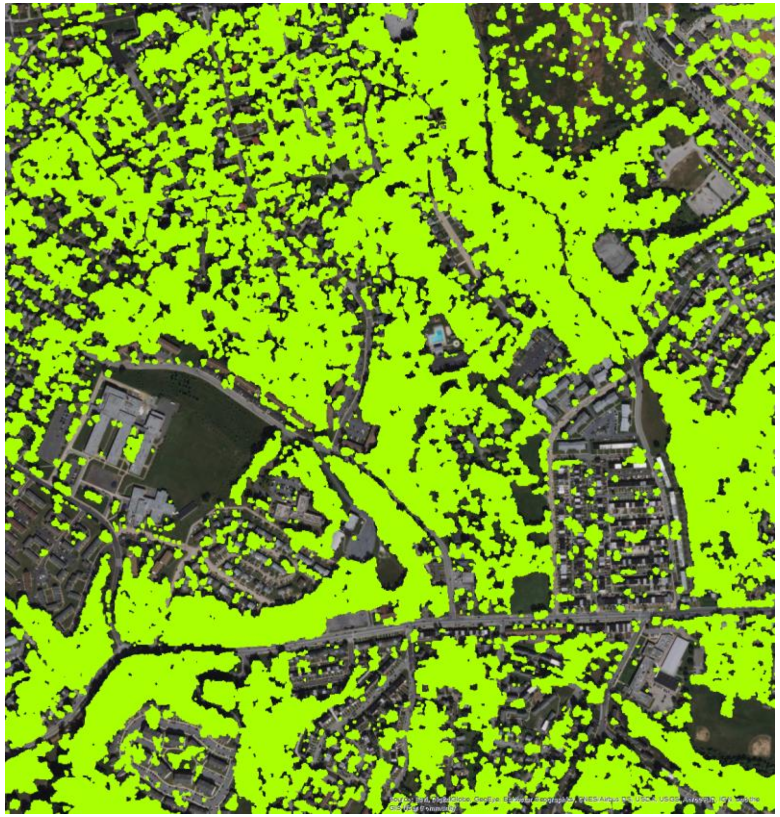
1. Tree canopy
2. Impervious surface
3. 3D built environment
4. Misc. physiography
5. Weather change
6. Spatial structure

Variable Name	Short name	Description
Vegetation		
Tree canopy	TCF	1 m tree canopy map derived from 2018 City of DC lidar data
Soft canopy	SCF	Tree canopy that does not overhang impervious surface
Hard canopy	HCF	Tree canopy that overhangs impervious surface
Canopy patches	PATCH	Soft canopy patches large enough to have cores (MSPA)
Distributed canopy	DISTRB	Soft canopy, connected or unconnected, no core (MSPA)
Pervious-open	PV-O	Area that is neither soft canopy nor impervious surface
Built Environment		
Impervious surface	IMP	Impervious surface from City of DC planimetric data
Building Height (sum)	BH	Building heights summed in area (DC building footprints and lidar data)
Building Height (IMP norm)	BH-norm	Building heights as above but normalized by IMP to decorrelate
Skyview Factor	SVF	Skyview factor calculated using DC lidar data in SAGA GIS
Physiographic		
Elevation	ELEV	City of DC lidar Digital Terrain Model (2018)
Quantile Elevation	Q-ELEV	Quantile (local) elevation within 300 m radius
Distance from water	DIST-W	Euclidean distance from Potomac and Anacostia rivers
Car data		
Spatial coordinates	LON, LAT	Temperature measurement locations geographic coordinates
Mobile temperature	MBL-T	Temperature measurements (celsius)
Miles per hour	MPH	Car travel speed
Station data		
Station Temperature	ST-T	Temperature (celsius) averaged across 4 downtown DC stations
Station Wind speed	ST-WS	Wind speed at one representative station
Station Wind direction	ST-WD	Wind speed at one representative station
Station Solar radiation	ST-SR	Solar radiation at one representative station

Methods: Canopy partitioning

Urban tree canopy

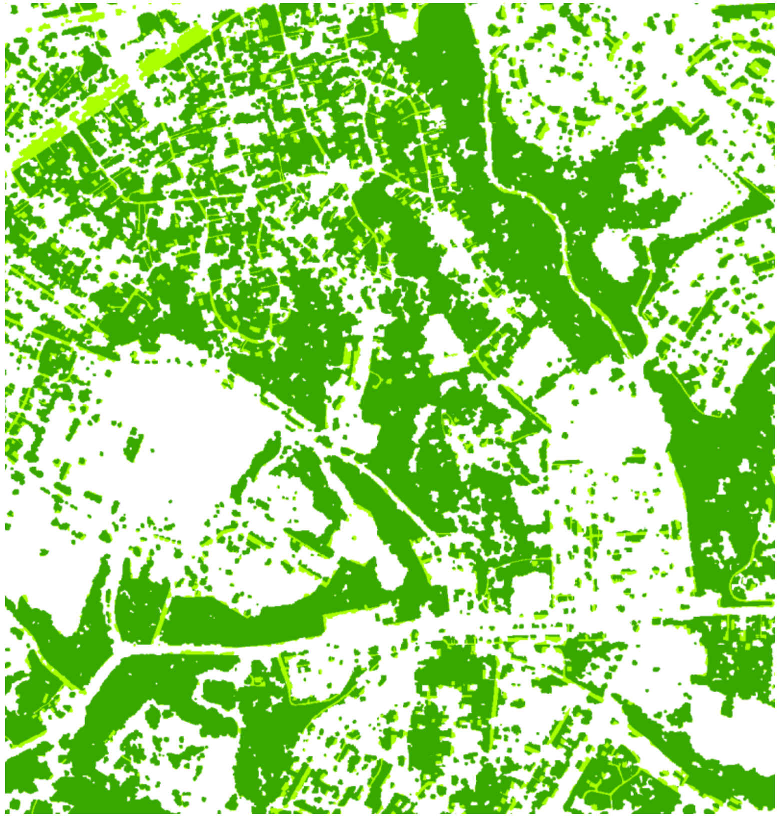
Derived from aerial imagery (2ft) and lidar canopy height model
Obscures urban surfaces for at least part of the day
Does not indicate soils with greater water holding capacity



Soft vs. hard canopy

Differentiates UTC over streets, buildings, sidewalks, parking lots from.

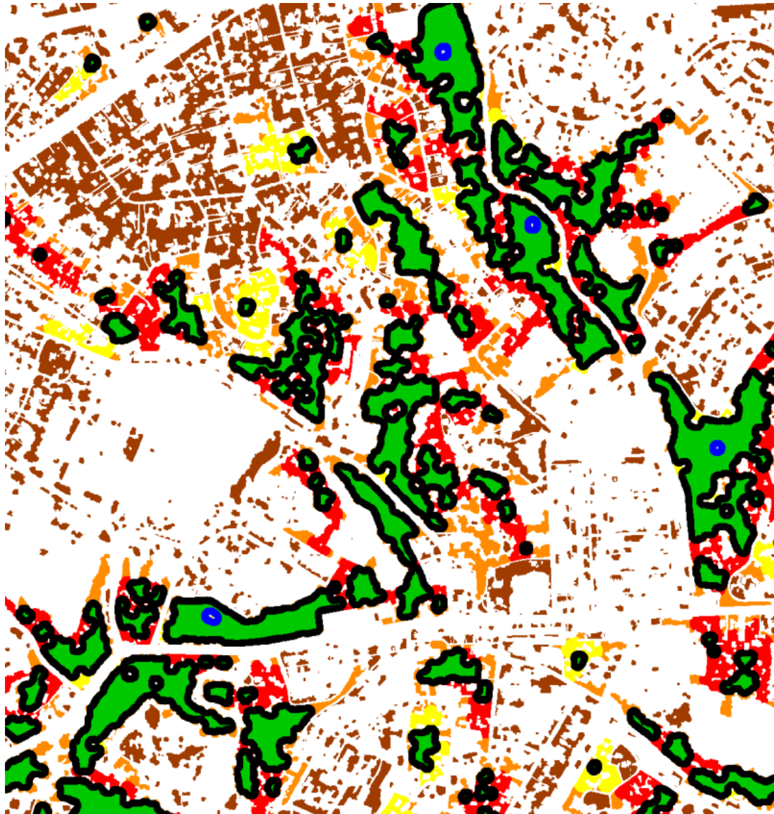
May reflect canopy variability in water holding capacity, but typically this requires interior woodland spaces



Patches vs. Distributed canopy

Using Morphological Spatial Pattern Analysis (MSPA), differentiate large patches with core (15 m edge) from other distributed canopy (edge only).

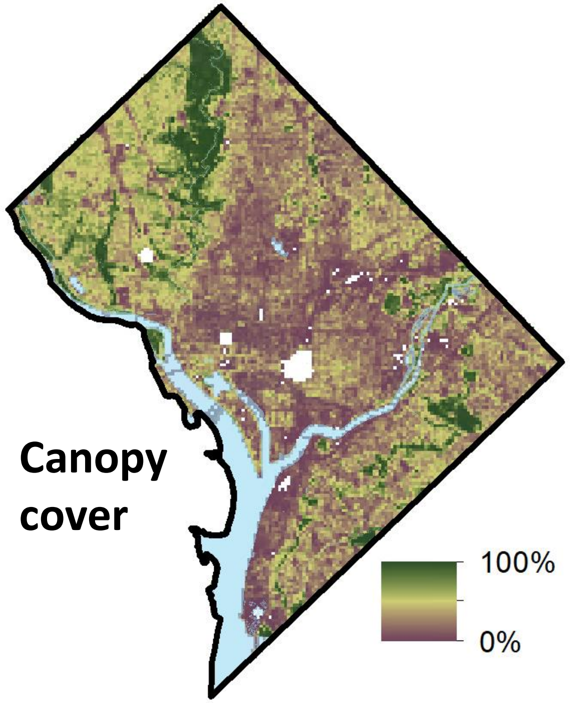
Ecological distinctions (soil, provenance)



Methods: Generalized Additive Models

GAMs are useful for flexible modeling of nonlinear relationships.

- Following on Ziter 2019 methods for comparison
- Split the difference between linear modeling (inflexible, lower variance explained, high interpretability) and machine learning (flexible, high variance explained, low interpretability)

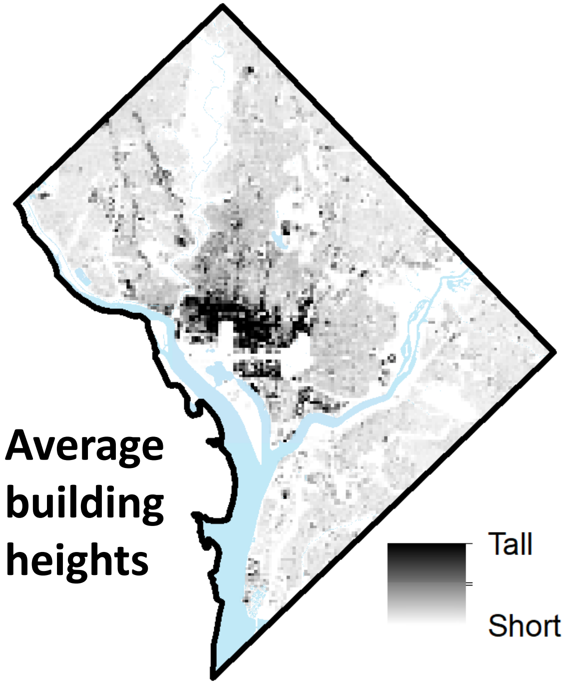


<u>Our models (all terms smoothed, 200 m):</u>

1. *T_a ~ tcf + imp + (tcf * imp) + elev + wind + (lon*lat)*

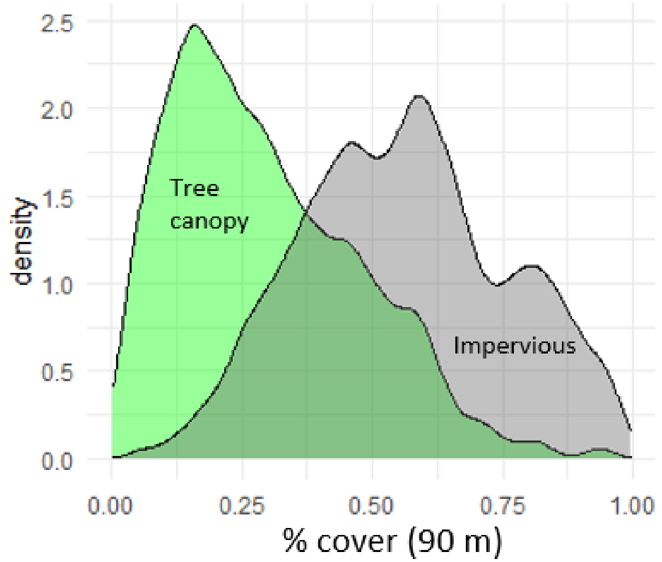
2. *T_a ~ scf + hcf + imp + (scf * imp) + elev + wind + (lon*lat)*

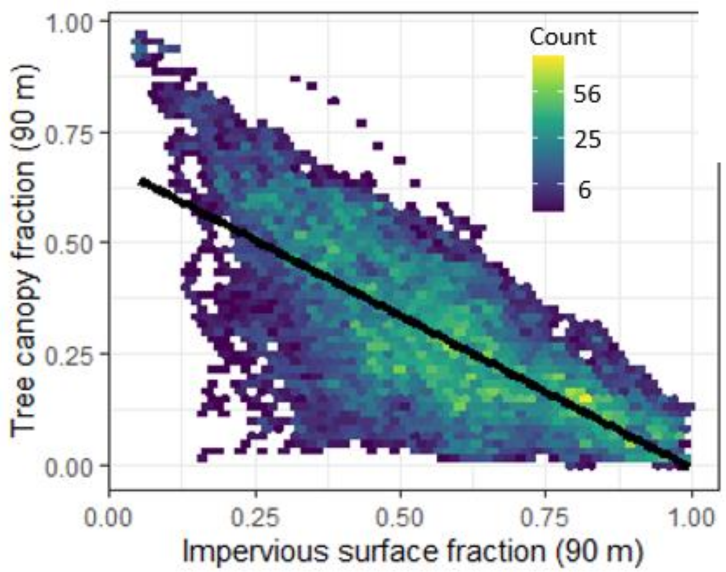
3. *T_a ~ patches + distrib + hcf + imp + (patches * imp) + elev + wind + (lon*lat)*

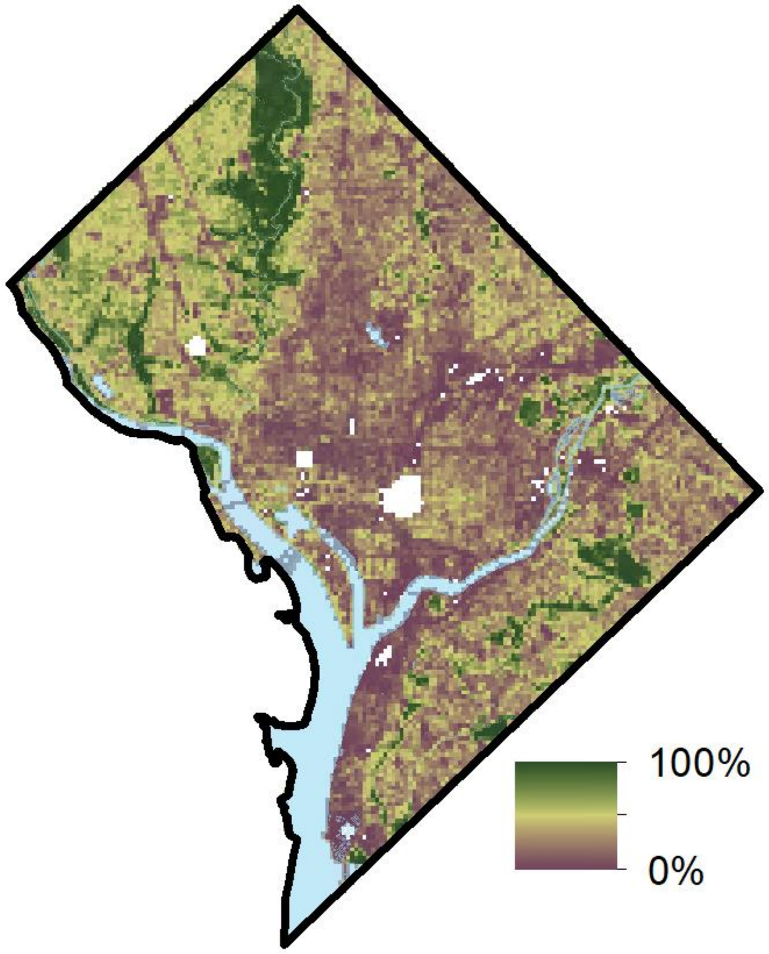


Results: The basics

- Tree canopy cover estimated at 38% (0% quantity disagreement, 91% OA)
- In our data collection we recorded 56% impervious and 29.5% canopy cover due to road-based sampling
- High inverse correlation between canopy cover and impervious surface in DC (r = -0.73 for TCF and -0.81 for SCF)





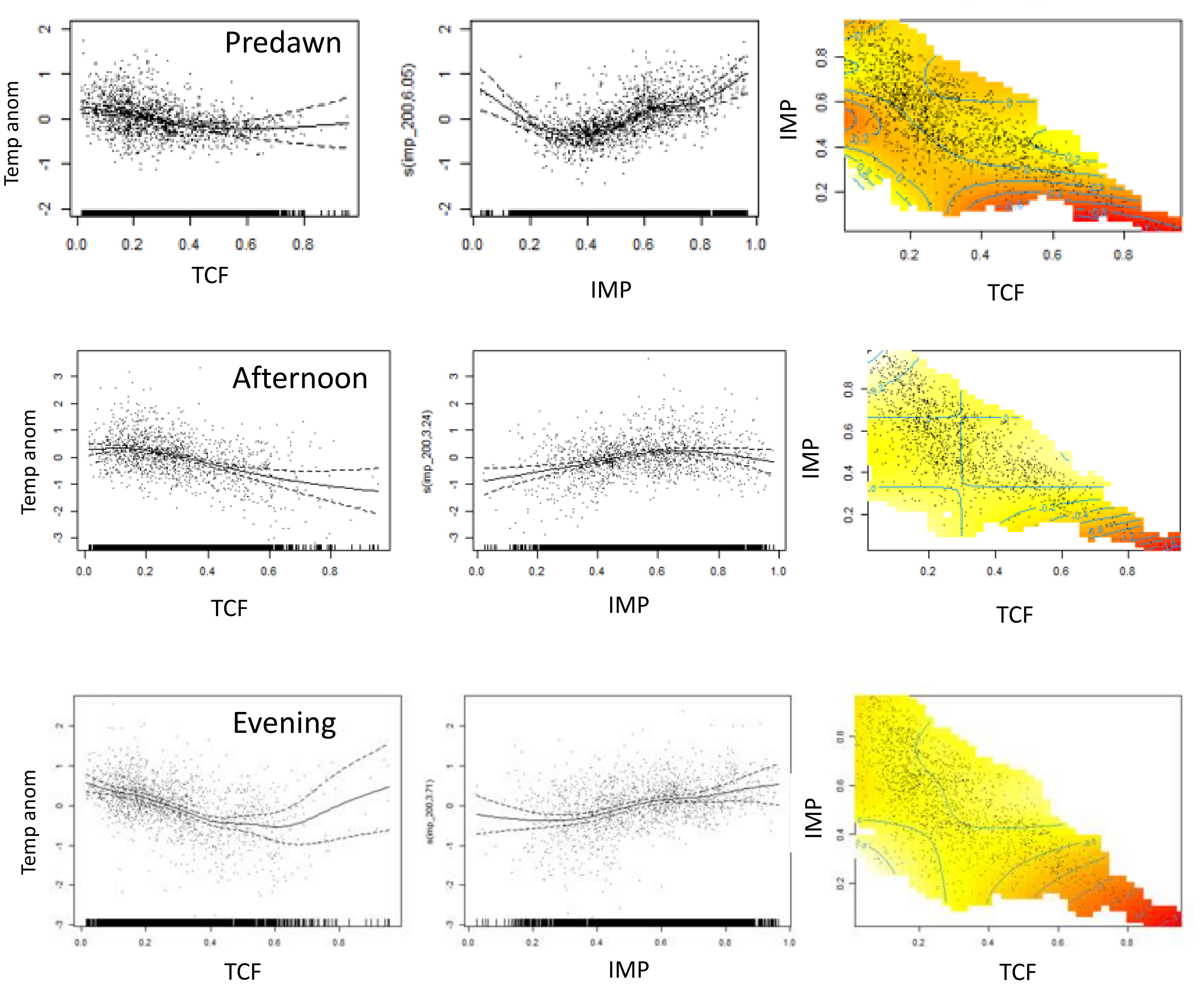


UTC Map (1 m resolution, Estimate = 38%, OA = 91% using leaf-off lidar)

Results: TCF and IMP

Model 1 key variables: TCF and IMP

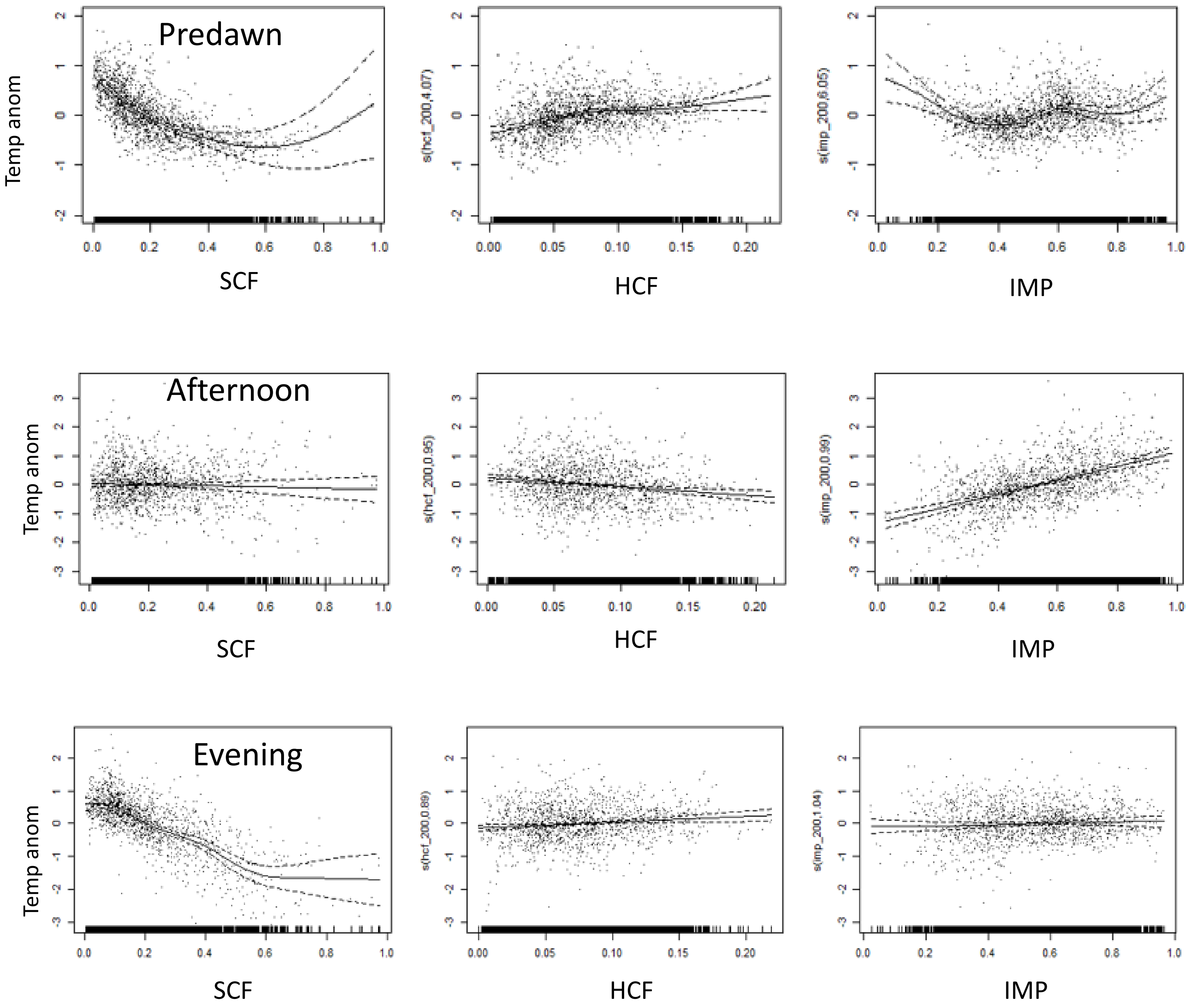
- Predawn warming from impervious surface
- Less model explanatory power in afternoon. Similar contributions to temp modification from canopy and impervious surface
- In the evening, strong cooling from both canopy and the interaction between canopy and impervious surface



Results: SCF, HCF, IMP

Model 2 key variables: Soft canopy, hard canopy, impervious

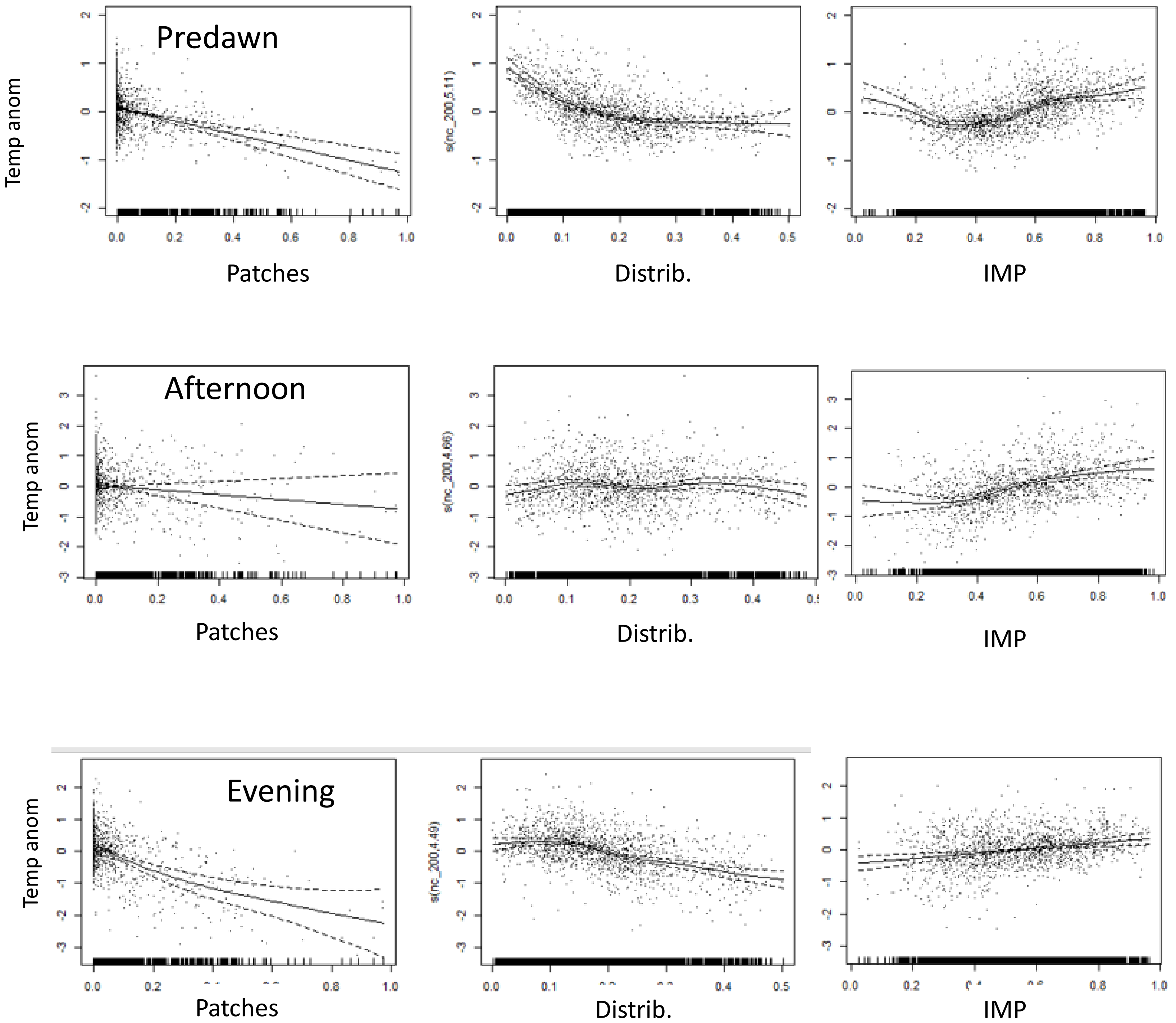
- Strong **predawn** cooling from SCF, even at low % cover. Warming partitioned between IMP and HCF.
- No discernible independent cooling effect from SCF in **afternoon** but strong cooling in interaction term. IMP important.
- In the **evening**, strong cooling from SCF even at lower cover % (less so in interaction term)



Results: Patches and Distrib.

Model 3 key variables: Forest patches, distributed canopy, impervious

- Patches cool strongly **predawn** but so does distributed canopy at low % cover
- Impervious-driven warming in **afternoon**. But also, strong cooling in patch*impervious term perhaps indicating inability of distrib to cool as well in high heat.
- In the **evening**, strong cooling from patches and noteworthy cooling from distrib, albeit at higher % cover.



Discussion

Where does an increase in tree cover give us the most cooling effect?

- The where depends on the *when*!
- Planting out any soft canopy category can lead to cooling of ~1 degree in predawn
- Maximizing cooling in the afternoon may occur when impervious surface can be replaced with soft canopy.
- Patch planting most impactful in evening but distributed has meaningful benefit and offers greater spatial access to cooling benefit.

	HCF	Patches	Distributed	Interaction
Predawn	-0.5	1	1.2	0.05
Afternoon	0.5	0.5	0.1	2
Evening	-0.2	1.5	1	0.3

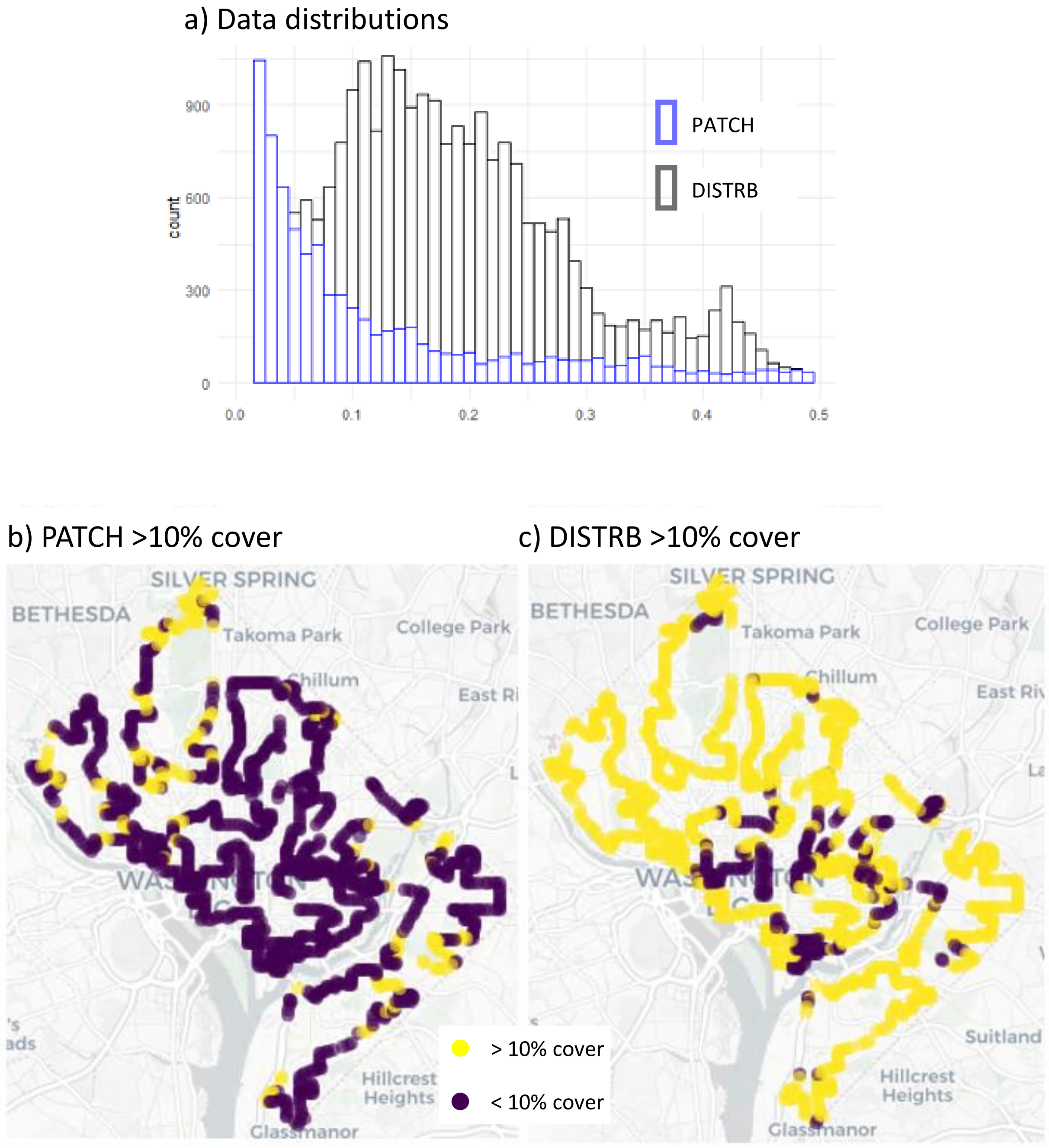
Attribution of cooling (or warming) by canopy subclass and time of day. Interaction term is forest patches * impervious only.

Values are reported over the range of reasonable cover percentages (e.g., patches to 60% cover)

Discussion

Opportunities Equitable Planting

- Previous findings using "tree canopy" (no subclasses) suggested 40% cover threshold as tipping point for temperature benefit (Ziter et al., 2019, PNAS)
- Not great for distributing the cooling benefit to those who need it →
- We find utility in distributed canopy suggesting that, e.g., backyard planting may be beneficial ("Riversmart Homes" co-benefit)



Potential future work

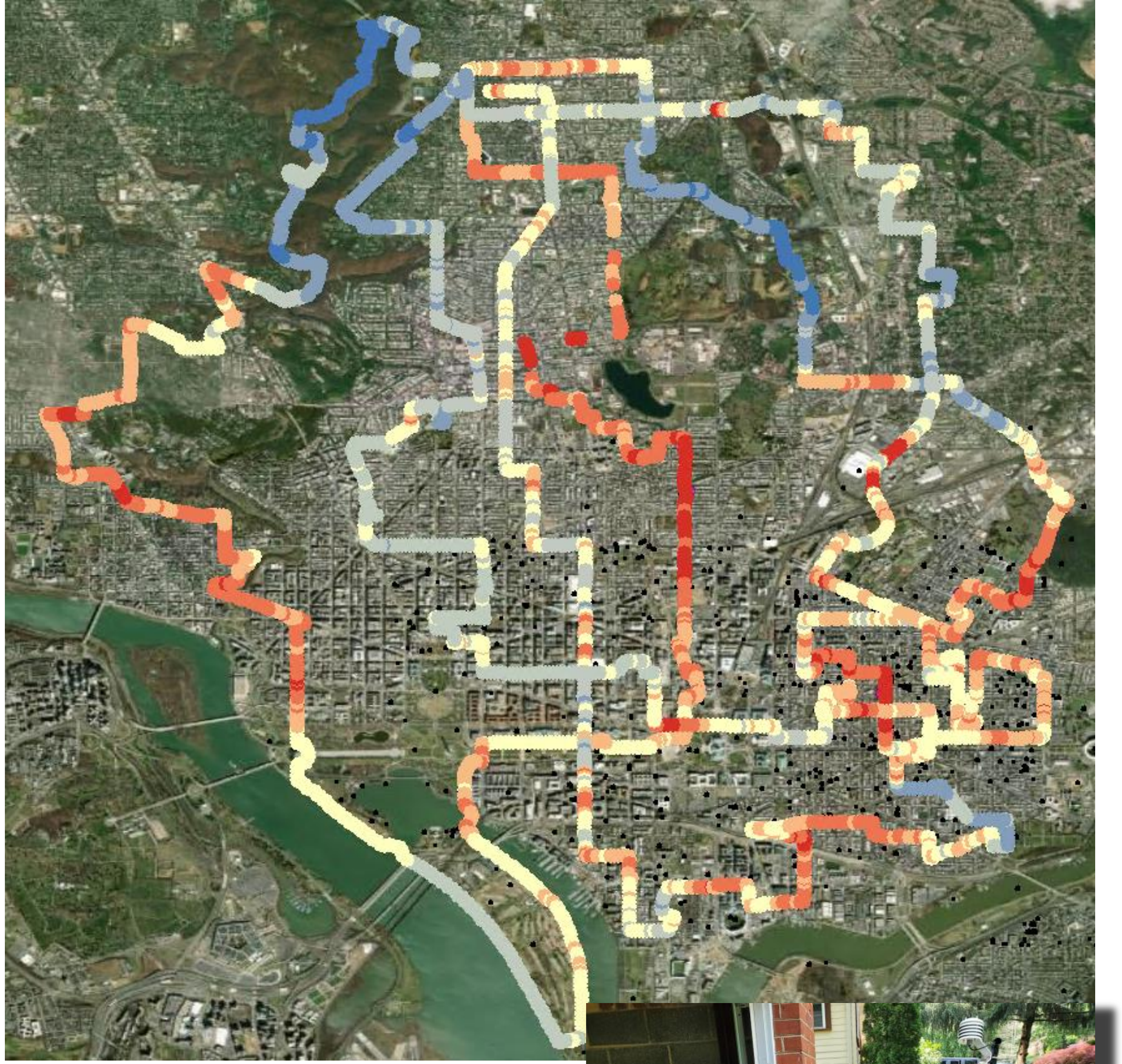
A few ideas but open for discussion:

- Follow up this study in Baltimore where there are more forest patches spread across the urban landscape (all important data already available)

- Revisit the temporal stability of the effects found in this study using a bike dataset collected Summer 2020 in DC

- Relate spatial variability in urban heat to alteration of urban tree phenology

- And…



Mike's bike setup and data from summer 2020 (2-4 pm rides paired with 4-6 am rides, ~21-mile loops)

Selected References

Jung, M. C., Dyson, K., & Alberti, M. (2021). Urban Landscape Heterogeneity Influences the Relationship between Tree Canopy and Land Surface Temperature. *Urban Forestry & Urban Greening*, *57*, 126930.

Shandas, V., Voelkel, J., Williams, J., & Hoffman, J. (2019). Integrating satellite and ground measurements for predicting locations of extreme urban heat. *Climate*, *7*(1), 5.

Shashua-Bar, L., Pearlmutter, D., & Erell, E. (2009). The cooling efficiency of urban landscape strategies in a hot dry climate. *Landscape and Urban Planning*, *92*(3-4), 179-186.

Ziter, C. D., Pedersen, E. J., Kucharik, C. J., & Turner, M. G. (2019). Scale-dependent interactions between tree canopy cover and impervious surfaces reduce daytime urban heat during summer. *Proceedings of the National Academy of Sciences*, *116*(15), 7575-7580.