Can spatial patterns mitigate the urban heat island effect? Evidence from German metropolitan regions

Wenzheng Li, Ph.D. Candidate
Stephan Schmidt, Associate Professor
City and regional planning, Cornell University

Introduction

- UHI effect: the thermal anomaly of higher temperature in urban areas compared with less densely populated rural areas.
- Multiple dimensions: urban vs. rural; diurnal vs. nocturnal period; warm vs. cold seasons
- Adverse impacts: raising energy consumption; air pollution; serious risks to human health (Debbage and Shepherd, 2015, Stone, 2012; Zhou and Shepherd, 2010).
- Spatial planning policy to address increasing challenge caused by severe heatwaves in Western Europe

NATURE AND ENVIRONMENT | FRANCE

Heat wave scorches western Europe

07/13/2022

France and the Iberian peninsula are struggling to contain wildfires while the UK is bracing itself for temperatures to hit a record 40 degrees Celsius. Climate change has been cited as the cause for the intense heat.

CNN World Africa Americas Asia Australia China Europe India Middle East United Kingdom

Germany's temperature record smashed as Europe's heat wave intensifies

By Ivana Kottasová, CNN
Updated 1:01 PM EDT, Wed June 26, 2019

Forbes

FORBES > BUSINESS

BREAKING

20,000 Died Amid Punishing Heatwaves And Record Temperatures Across Western Europe This Summer, Data Indicates

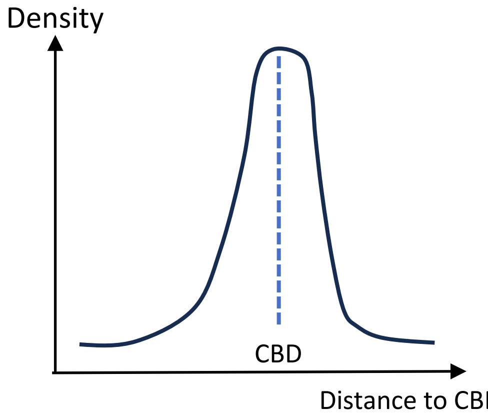
The effects of urban spatial patterns on the UHI effect

- Traditional wisdom:
  - **Denser and compact** urban development -> greater UHI intensities.
    - mechanisms contributing to heat accumulation are amplified in denser urban areas (Couts et al., 2007; Debbage and Shepherd, 2015).
  - **Sprawling, low-density and fragmented** development -> exacerbate UHI intensities.
    - impervious surface coverage, energy consumption (Ewing and Rong, 2008; Shreevastava et al., 2019).

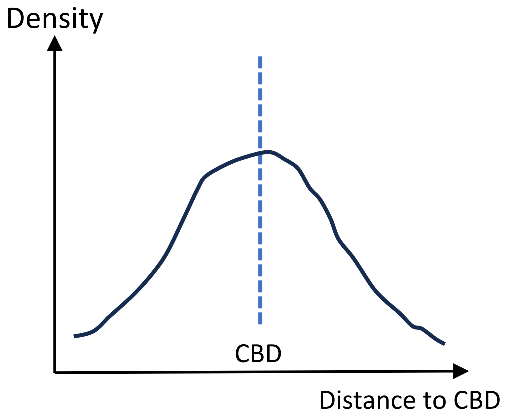
- A dilemma in regional and spatial planning policy:
  - Is high-density and compact growth a viable mitigation strategy or will it make cities less livable?

Polycentric spatial development (polycentrism)

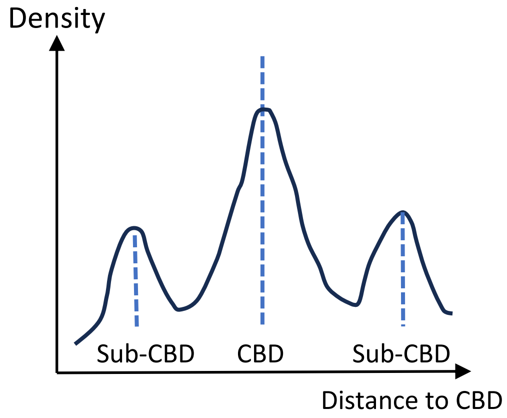
- Reconciles this dilemma (dichotomy)?
  - Multiple centers, balanced structure, network of interconnections
  - integrate the benefits of both compact and dispersed development (Meijers and Burger, 2010)
    - “**Decentralization**”: less concentrated around a single center
    - “**Compactness**”: decentralized activities re-agglomerate outside urban core
  - Lower density in urban cores; high-density design; reduced energy consumption



Compact and monocentric development



Sprawling and decentralized development

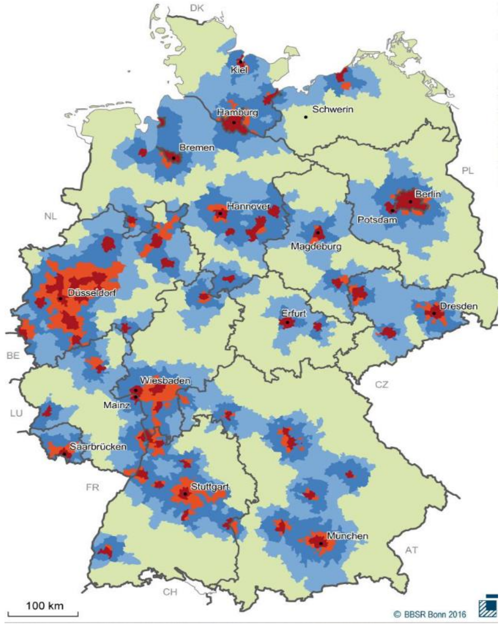


Polycentric development

Research objectives:

- By examining the UHI intensities of 50 metropolitan regions in Germany with various landscape/urban spatial structure metrics, this study aims to:
    - evaluate the degree to which traditional urban spatial patterns, including measures of land-use composition, fragmentation, and shape complexity, influence the UHI effect.
    - investigate the capacity of a polycentric spatial pattern, characterized by features of disaggregation and compactness, to mitigate urban heat.

German Regions



Berlin/Potsdam

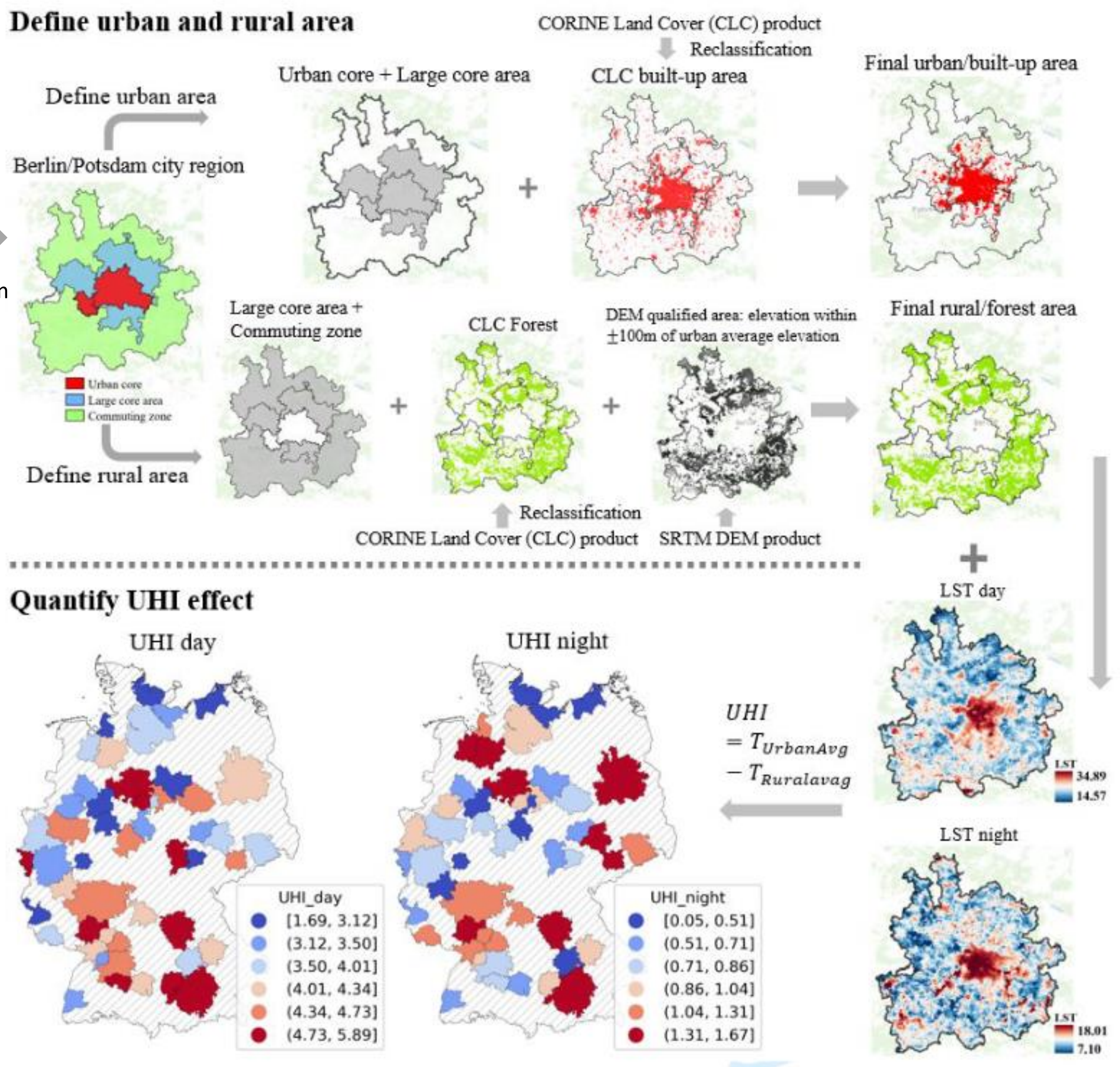


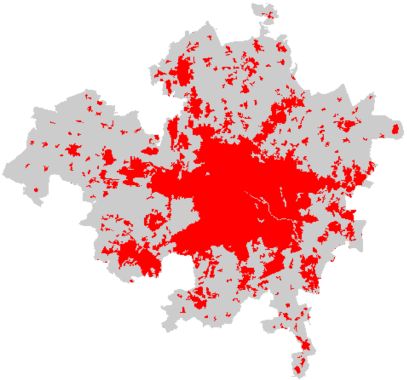
Figure 1: the illustrations of urbanized and rural areas delineation (step 1) and the quantification of the urban heat island (UHI) effect (step 2).

- **Area:** 50 functional city-regions
- **Data:**
  - Land surface temperature (LST)
    - in June, July, August
    - MODIS Aqua satellite 1km.
    - Collect 1:30PM and 1:30AM
  - CORINE Land Cover
  - SRTM DEM

Spatial metrics for urban spatial patterns

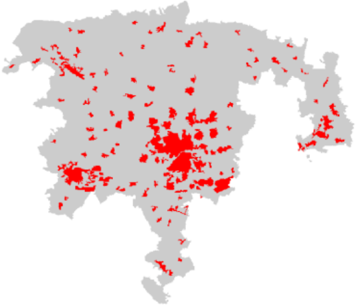
Fragmentation

Berlin/Potsdam



Patch density (PD): 0.228
Percentage of like adjacencies (PLADJ): 91.117

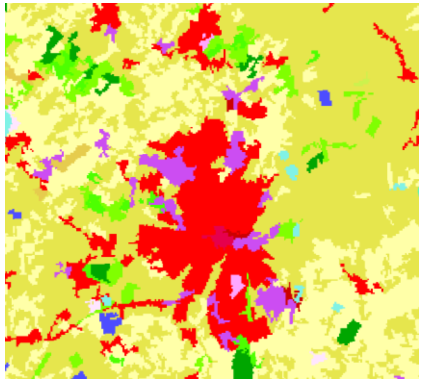
Ingolstadt



Patch density (PD): 0.872
Percentage of like adjacencies (PLADJ): 83.86

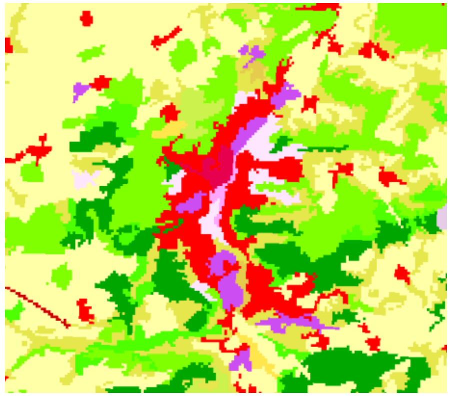
Mixed land use

Oldenburg



Contagion index: 38.22

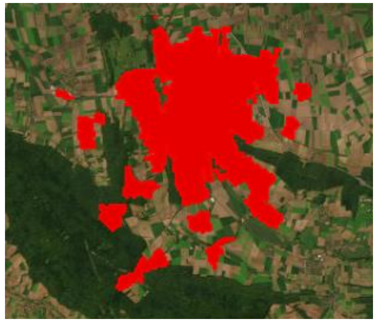
Jena



Contagion index: 62.99

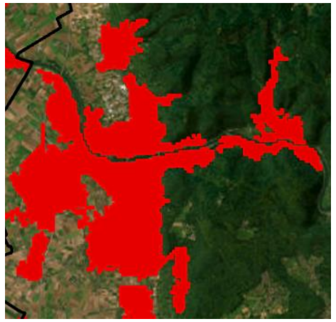
Shape complexity:

Hildesheim



Area-weighted mean shape index (AWMSI): 1.67

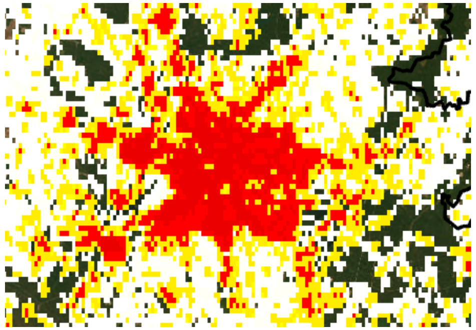
Heidelberg



Area-weighted mean shape index (AWMSI): 2.18

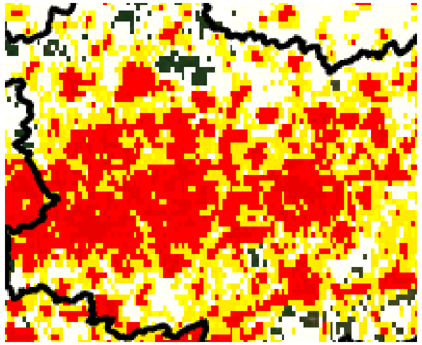
Polycentricity index:

Berlin/Potsdam



Polycentricity index: 0.375

Essen/Bochum/Dortmund/Hagen



Polycentricity index: 0.892

Regression analysis (cross-sectional analysis)

$$UHI_i = c + \beta_1 SPM_i + \boldsymbol{\mu Z_i} + \epsilon_i$$

- SPM_i is one of the urban spatial pattern measures for region i.
- The vector $\boldsymbol{Z_i}$ contains a set of UHI control variables: population density, windspeed of summer season, and a drought index derived from temperature and precipitation.

Assumption: large regions reap greater benefits from polycentrism than smaller regions

$$\text{UHI}_i = c + \gamma_1 POLY_i \times PopSize_i + \boldsymbol{\delta Z_i} + \epsilon_i$$

- $PopSize$: a categorical variable, classifying regions into three equal-sized groups.
- $\gamma 1$: captures the varying effects of polycentricity on the UHI effect, moderating by population size

Data sources: Population: INKAR; windspeed (JJA): ERA5 monthly averaged data; Drought index in summer: Deutscher Wetterdienst

The influence of traditional landscape metrics on the UHI effect

For urban patches

- **PLADJ_urban:** ↑ aggregation and contiguity → ↑ **UHI**

Table 3: regressions investigate the effects of landscape metrics on the day- or night-time urban heat island (UHI) effects in 2012.

Panel A: the effect of urban landscape metrics on the UHI effects

	UHI (ln) at Day				UHI (ln) at Night			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
PLADJ_Urban	.057***				.11***			
	(.009)				(.032)			
PD (ln)		-.286***				-.695***		
		(.063)				(.199)		
CONTAG (ln)			-.877***				-.774	
			(.303)				(.94)	
AWMSI (ln)				.225***				.483**
				(.079)				(.201)
Popdensity (ln)	-.068	-.063	.082	.12	.131	.003	.557	.478
	(.142)	(.14)	(.121)	(.139)	(.356)	(.294)	(.377)	(.335)
Windspeed (ln)	-.7***	-.705***	-.431***	-.662***	-.216	-.336	-.089	-.268
	(.118)	(.142)	(.131)	(.153)	(.232)	(.215)	(.253)	(.254)
Drought (ln)	-.095	-.147	-.178	-.164	-.072	-.225	-.247	-.296
	(.093)	(.097)	(.119)	(.109)	(.223)	(.247)	(.221)	(.23)
Constant	-2.633***	2.152**	4.71***	.623	-2.861***	.338	2.38	-.121
	(.898)	(1.058)	(1.741)	(1.04)	(.788)	(.733)	(1.846)	(.779)
Observations	49	49	49	49	49	49	49	49
R-squared	.48	.472	.377	.371	.429	.372	.267	.35

Panel B: the effects of greenspace landscape metrics on UHI effects

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	(.009)		(.017)	
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- **ROV:** ↑ vegetated coverage → ↓UHI

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Drought (ln)	-.095	-.147	-.178	-.164	-.072	-.225	-.247	-.296
	(.093)	(.097)	(.119)	(.109)	(.223)	(.247)	(.221)	(.23)
Constant	-2.633***	2.152**	4.71***	.623	-2.861***	.338	2.38	-.121
	(.898)	(1.058)	(1.741)	(1.04)	(.788)	(.733)	(1.846)	(.779)
Observations	49	49	49	49	49	49	49	49
R-squared	.48	.472	.377	.371	.429	.372	.267	.35

Panel B: the effects of greenspace landscape metrics on UHI effects

	UHI (ln) at Day		UHI (ln) at Night	
	Model 1	Model 2	Model 3	Model 4
PLADJ_Green	.024**		.061***	
	(.009)		(.017)	
ROV (ln)		-.309***		-.611***
		(.085)		(.185)
Popdensity (ln)	.186	.229*	.571*	.717**
	(.138)	(.118)	(.317)	(.298)
Windspeed (ln)	-.638***	-.753***	-.298	-.267
	(.153)	(.13)	(.241)	(.233)
Drought (ln)	-.205*	-.151	-.379	-.188
	(.105)	(.102)	(.238)	(.226)
Constant	-1.275	-.096	-8.721***	-6.01**
	(1.076)	(.929)	(2.66)	(2.362)
Observations	49	49	49	49
R-squared	.366	.451	.263	.303

*Robust standard errors are in parentheses; *** p<.01, ** p<.05, * p<.1*

(1) Observations removed due to the extremely low UHI (ln) values: the region of Siegen in daytime models, and the region of Ingolstadt in nighttime models.

The influence of polycentric development on the UHI effect

- Polycentricism: ↑ **polycentricity,** ↓ **UHI** effect for large-sized regions.
- Mitigation effect:
  - most pronounced closer to the urban center(s);
  - gradually diminishes as the distance from CBDs.

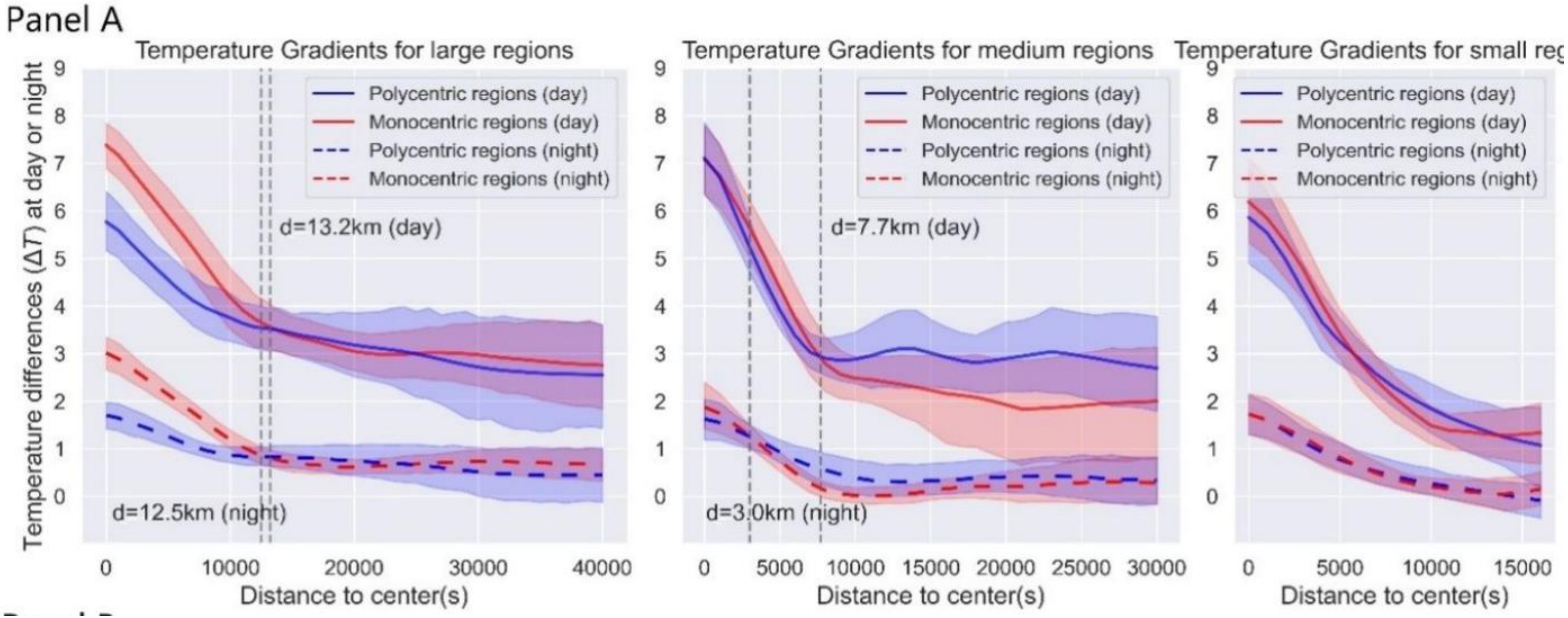
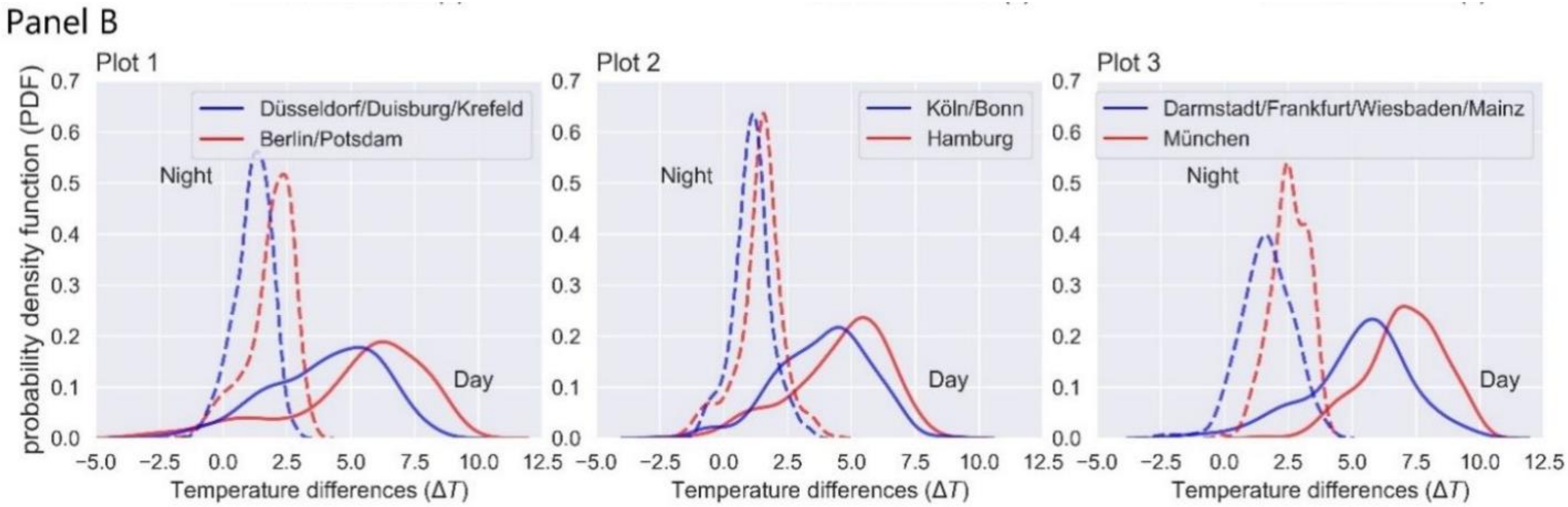


Figure 3, Panel A: day- and night-time temperature gradients in large-, medium-, and small-sized regions estimated by local weighted regression.

The influence of polycentric development on the UHI effect

- Three selected pairs of regions
- kernel density estimates
- Monocentric regions: higher peak values shifted towards the right
  - a greater proportion of high-temperature areas



Panel B: day- and night-time kernel density estimates (KDE) for three representative region pairs using Gaussian kernel. Red depicts monocentric regions and blue polycentric regions.

The influence of polycentric development on the UHI effect

- Models 5 and 6: ↑ **polycentricity,↓ UHI**

	$UHI(\ln) = T_{Core(mean)} - T_{R(mean)}$			
	Model 5 Day	Model 6 Day	Model 7 Night	Model 8 Night
Poly (ln)	-.1027** (.0411)	.0445 (.1044)	-.2568* (.1357)	.2109 (.2728)
Poly(ln)*Medium		-.1796 (.1707)		-.2952 (.4604)
Poly(ln)*Large		-.1848* (.1086)		-.5709 (.369)
Medium Regions		-.0685 (.1076)		-.0708 (.2715)
Large Regions		-.0747 (.0989)		.0628 (.2561)
Popdensity (ln)	-.2233 (.1681)	-.2594 (.1826)	.1489 (.3508)	-.0968 (.3397)
WindSpeed (ln)	-.6989*** (.1862)	-.6563*** (.1991)	-.2339 (.2121)	-.2311 (.2022)
Drought (ln)	-.0482 (.1249)	-.052 (.1334)	-.0264 (.2837)	-.0035 (.2689)
PLADJ_urban	.0313*** (.0113)	.0299** (.0116)	.0567* (.0322)	.031 (.0309)
CONTAG (ln)	-.4311 (.3229)	-.4414 (.3724)	.5509 (.7548)	1.1082 (.7336)
constant	2.579 (2.1476)	3.0892 (2.357)	-8.320 (5.455)	-6.2968 (5.1748)
Observations	49	49	49	49
R-squared	.3732	.4002	.2071	.4016

The influence of polycentric development on the UHI effect

- Models 5 and 6: ↑ **polycentricity,**↓ **UHI**
- Model 6: interaction term
  - Polycentricism is more effective in mitigating UHI effect of larger regions

$UHI(\ln) = T_{Core(mean)} - T_{R(mean)}$

	Model 5 Day	Model 6 Day	Model 7 Night	Model 8 Night
Poly (ln)	-.1027**	.0445	-.2568*	.2109
	(.0411)	(.1044)	(.1357)	(.2728)
Poly(ln)*Medium		-.1796		-.2952
		(.1707)		(.4604)
Poly(ln)*Large		-.1848*		-.5709
		(.1086)		(.369)
Medium Regions		-.0685		-.0708
		(.1076)		(.2715)
Large Regions		-.0747		.0628
		(.0989)		(.2561)
Popdensity (ln)	-.2233	-.2594	.1489	-.0968
	(.1681)	(.1826)	(.3508)	(.3397)
WindSpeed (ln)	-.6989***	-.6563***	-.2339	-.2311
	(.1862)	(.1991)	(.2121)	(.2022)
Drought (ln)	-.0482	-.052	-.0264	-.0035
	(.1249)	(.1334)	(.2837)	(.2689)
PLADJ_urban	.0313***	.0299**	.0567*	.031
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	(.3229)	(.3724)	(.7548)	(.7336)
constant	2.579	3.0892	-8.320	-6.2968
	(2.1476)	(2.357)	(5.455)	(5.1748)
Observations	49	49	49	49
R-squared	.3732	.4002	.2071	.4016

Conclusion and policy implication

- **Local land-use policy:**
  - Facilitate more mixed land-use, more regularly-shaped urban spatial pattern

- **Local greenspace planning:**
  - Several small better than a single large
  - More dispersed distribution of greenspace: reduce urban aggregation, decrease the overall density of urban cores

- **Regional scale planning:**
  - Facilitate the development of polycentric urban regions (PURs)
    - particularly advantageous in cooling **large-sized regions** and **CBD(s)**
      - reduce density of urban core(s);
      - facilities disaggregated urban development;
      - curb excessive expansion of impervious surface.

Thank you!

Comments and Suggestions

Wenzheng Li, wl563@cornell.edu
Stephan Schmidt, sjs96@cornell.edu

The influence of polycentric development on the UHI effect

Two definitions of the UHI effect

- M1-4: $\Delta T = T_{extent} - T_{rural}$
- M5-8: $\Delta T = T_{core} - T_{rural}$

M1-4

- statistical significance in Model 1
- interaction terms insignificant

Table 4: regressions examine the impacts of polycentric development on the day- and night-time UHI effects in 2012.

	$UHI(\ln) = T_{LargeCore(mean)} - T_{R(mean)}$				$UHI(\ln) = T_{Core(mean)} - T_{R(mean)}$			
	Model 1 Day	Model 2 Day	Model 3 Night	Model 4 Night	Model 5 Day	Model 6 Day	Model 7 Night	Model 8 Night
Poly (ln)	-.0654*	-.0686	-.175	.0492	-.1027**	.0445	-.2568*	.2109
	(.0351)	(.094)	(.1419)	(.3174)	(.0411)	(.1044)	(.1357)	(.2728)
Poly(ln)*Medium		.069		.0325		-.1796		-.2952
		(.1417)		(.521)		(.1707)		(.4604)
Poly(ln)*Large		-.0122		-.3078		-.1848*		-.5709
		(.1023)		(.3699)		(.1086)		(.369)
Medium Regions		.0749		.0856		-.0685		-.0708
		(.0987)		(.3072)		(.1076)		(.2715)
Large Regions		-.008		.0248		-.0747		.0628
		(.0917)		(.2899)		(.0989)		(.2561)
Popdensity (ln)	-.1664	-.1597	.1049	-.0229	-.2233	-.2594	.1489	-.0968
	(.1323)	(.1421)	(.3669)	(.3952)	(.1681)	(.1826)	(.3508)	(.3397)
WindSpeed (ln)	-.6867***	-.6607***	-.2105	-.221	-.6989***	-.6563***	-.2339	-.2311
	(.1289)	(.1543)	(.2218)	(.2353)	(.1862)	(.1991)	(.2121)	(.2022)
Drought (ln)	-.1111	-.1194	-.0607	-.0566	-.0482	-.052	-.0264	-.0035
	(.104)	(.1147)	(.2968)	(.3128)	(.1249)	(.1334)	(.2837)	(.2689)
PLADJ_urban	.049***	.0505***	.1033***	.0903**	.0313***	.0299**	.0567*	.031
	(.0086)	(.0082)	(.0337)	(.036)	(.0113)	(.0116)	(.0322)	(.0309)
CONTAG (ln)	-.612*	-.6276*	-.276	.0679	-.4311	-.4414	.5509	1.1082
	(.3098)	(.3623)	(.7895)	(.8535)	(.3229)	(.3724)	(.7548)	(.7336)
constant	1.2647	1.1339	-9.012	-8.2142	2.579	3.0892	-8.320	-6.2968
	(1.7476)	(1.9141)	(5.7056)	(6.0205)	(2.1476)	(2.357)	(5.455)	(5.1748)
Observations	49	49	49	49	49	49	49	49
R-squared	.537	.5455	.3362	.3801	.3732	.4002	.2071	.4016

*Robust standard errors are in parentheses; *** p<.01, ** p<.05, * p<.1*

(1) Observations removed due to the extremely low UHI (ln) values: the region of Siegen in daytime models, and the region of Ingolstadt in nighttime models.

The influence of polycentric development on the UHI effect

Two definitions of the UHI effect

- M1-4: $\Delta T = T_{extent} - T_{rural}$
- M5-8: $\Delta T = T_{core} - T_{rural}$

M1-4

- statistical significance in Model 1
- interaction terms insignificant

M5-8

- M5, M6: significant
- ↓ **UHI** within the urban core(s) rather than the extended large core area.

Table 4: regressions examine the impacts of polycentric development on the day- and night-time UHI effects in 2012.

	$UHI(\ln) = T_{LargeCore(mean)} - T_{R(mean)}$				$UHI(\ln) = T_{Core(mean)} - T_{R(mean)}$			
	Model 1 Day	Model 2 Day	Model 3 Night	Model 4 Night	Model 5 Day	Model 6 Day	Model 7 Night	Model 8 Night
Poly (ln)	-.0654*	-.0686	-.175	.0492	-.1027**	.0445	-.2568*	.2109
	(.0351)	(.094)	(.1419)	(.3174)	(.0411)	(.1044)	(.1357)	(.2728)
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		(.1023)		(.3699)		(.1086)		(.369)
Medium Regions		.0749		.0856		-.0685		-.0708
		(.0987)		(.3072)		(.1076)		(.2715)
Large Regions		-.008		.0248		-.0747		.0628
		(.0917)		(.2899)		(.0989)		(.2561)
Popdensity (ln)	-.1664	-.1597	.1049	-.0229	-.2233	-.2594	.1489	-.0968
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	(.0086)	(.0082)	(.0337)	(.036)	(.0113)	(.0116)	(.0322)	(.0309)
CONTAG (ln)	-.612*	-.6276*	-.276	.0679	-.4311	-.4414	.5509	1.1082
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constant	1.2647	1.1339	-9.012	-8.2142	2.579	3.0892	-8.320	-6.2968
	(1.7476)	(1.9141)	(5.7056)	(6.0205)	(2.1476)	(2.357)	(5.455)	(5.1748)
Observations	49	49	49	49	49	49	49	49
R-squared	.537	.5455	.3362	.3801	.3732	.4002	.2071	.4016

*Robust standard errors are in parentheses; *** p<.01, ** p<.05, * p<.1*

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The influence of polycentric development on the UHI effect

Two definitions of the UHI effect

- M1-4: $\Delta T = T_{extent} - T_{rural}$
- M5-8: $\Delta T = T_{core} - T_{rural}$

M1-4

- statistical significance in Model 1
- interaction terms insignificant

M5-8

- M5, M6: significant
- ↓ **UHI** within the urban core(s) rather than the extended large core area.
- M7: interaction term significant
- Polycentricism is more effective in mitigating UHI effect of larger regions

Table 4: regressions examine the impacts of polycentric development on the day- and night-time UHI effects in 2012.

	$UHI(\ln) = T_{LargeCore(mean)} - T_{R(mean)}$				$UHI(\ln) = T_{Core(mean)} - T_{R(mean)}$			
	Model 1 Day	Model 2 Day	Model 3 Night	Model 4 Night	Model 5 Day	Model 6 Day	Model 7 Night	Model 8 Night
Poly (ln)	-.0654*	-.0686	-.175	.0492	-.1027**	.0445	-.2568*	.2109
	(.0351)	(.094)	(.1419)	(.3174)	(.0411)	(.1044)	(.1357)	(.2728)
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		(.1417)		(.521)		(.1707)		(.4604)
Poly(ln)*Large		-.0122		-.3078		-.1848*		-.5709
		(.1023)		(.3699)		(.1086)		(.369)
Medium Regions		.0749		.0856		-.0685		-.0708
		(.0987)		(.3072)		(.1076)		(.2715)
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		(.0917)		(.2899)		(.0989)		(.2561)
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	(.1289)	(.1543)	(.2218)	(.2353)	(.1862)	(.1991)	(.2121)	(.2022)
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PLADJ_urban	.049***	.0505***	.1033***	.0903**	.0313***	.0299**	.0567*	.031
	(.0086)	(.0082)	(.0337)	(.036)	(.0113)	(.0116)	(.0322)	(.0309)
CONTAG (ln)	-.612*	-.6276*	-.276	.0679	-.4311	-.4414	.5509	1.1082
	(.3098)	(.3623)	(.7895)	(.8535)	(.3229)	(.3724)	(.7548)	(.7336)
constant	1.2647	1.1339	-9.012	-8.2142	2.579	3.0892	-8.320	-6.2968
	(1.7476)	(1.9141)	(5.7056)	(6.0205)	(2.1476)	(2.357)	(5.455)	(5.1748)
Observations	49	49	49	49	49	49	49	49
R-squared	.537	.5455	.3362	.3801	.3732	.4002	.2071	.4016

*Robust standard errors are in parentheses; *** p<.01, ** p<.05, * p<.1*

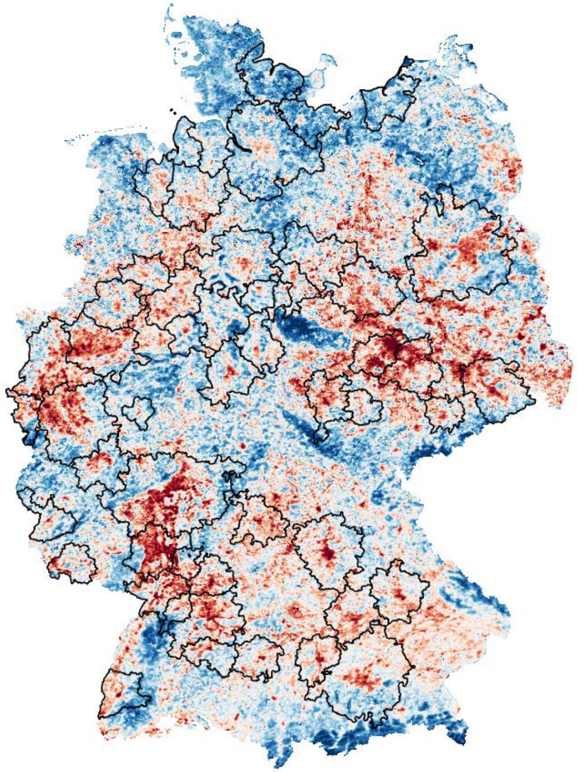
(1) Observations removed due to the extremely low UHI (ln) values: the region of Siegen in daytime models, and the region of Ingolstadt in nighttime models.

Land surface temperature (LST)

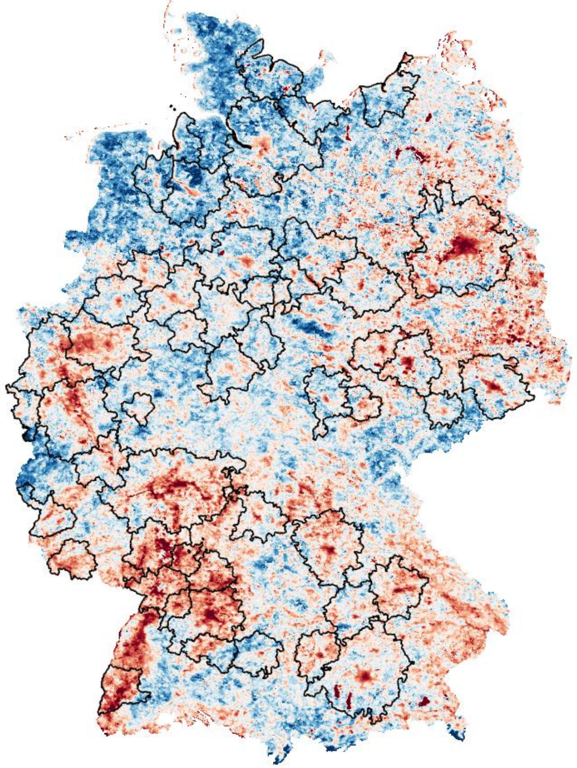
Mean land surface temperature (LST) in June, July, August :

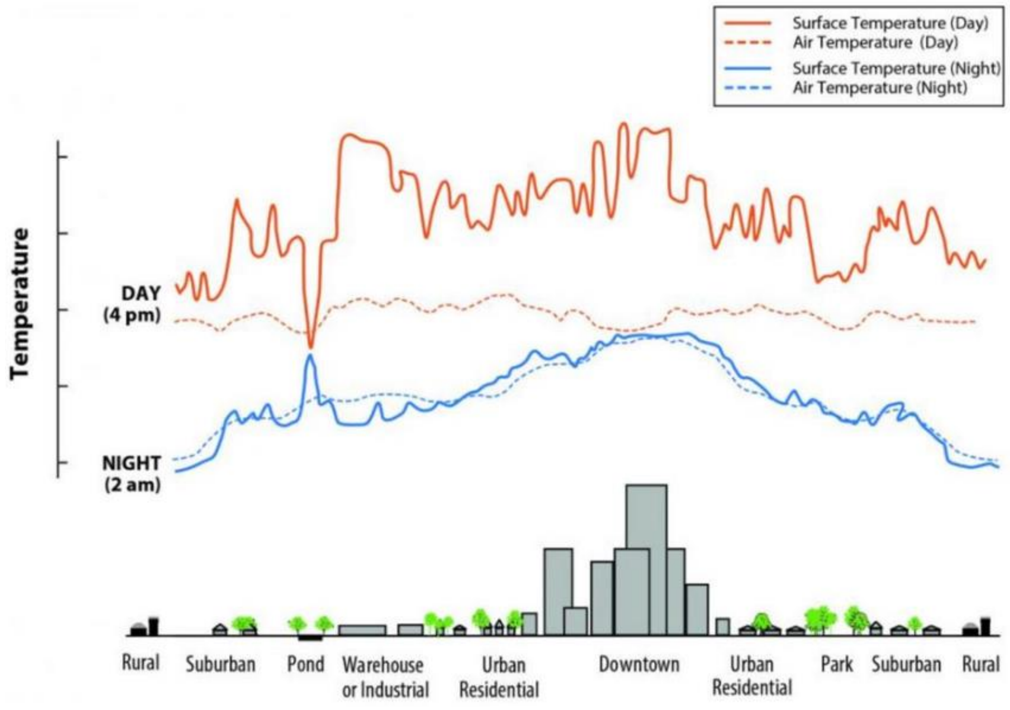
- MYD11A2.061 Aqua Land Surface Temperature and Emissivity 8-Day Global 1km.
- Available at 1:30 PM (day) and 1:30AM (night)

LST Day - 1:30 PM



LST Night - 1:30 AM





Credit: U.S. Environmental Protection Agency

Table 2: Descriptive statistics and data sources of variables collected for the year 2012 (*N*=49).

Variables	Mean	Std. Dev.	Median	Min	Max
Dependent variables					
UHI_day	3.995	.868	4.076	2.013	5.885
UHI_night	.929	.388	0.878	.176	1.668
Variables of interest					
PLADJ_urban	87.566	2.165	87.568	82.022	91.983
PD	.43	.192	0.365	.177	.958
CONTAG	53.362	5.299	52.388	44.904	63.99
AWMSI	5.198	2.055	4.478	2.635	11.002
PLADJ_Green	76.88	3.193	77.194	70.142	82.143
ROV	.53	.157	0.528	.156	.8
POLY	.617	.299	0.553	.218	1.597
Control variables					
Popdensity	2969.675	669.403	2738.377	1817.403	4567.669
Windspeed_day	1.438	.256	1.466	1.051	2.24
Windspeed_night	.745	.226	0.725	.335	1.317
Drought index	8.396	1.771	8.000	5	14

Data sources:
1. The MODIS LST product to measure the UHI effect: https://lpdaac.usgs.gov/products/myd11a2v061/.
2. Land-use dataset to generate landscape metrics: https://land.copernicus.eu/pan-european/corine-land-cover
3. Municipality population to quantify polycentricity index (POLY): INKAR (https://www.inkar.de/)
4. ERA5 monthly averaged data for day- and night-time windspeed in summer (June, July, and August): https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=fo
5. Drought index in summer: Deutscher Wetterdienst, https://opendata.dwd.de/climate_environment/CDC/grids_germany/

The influence of landscape metrics on the UHI effect

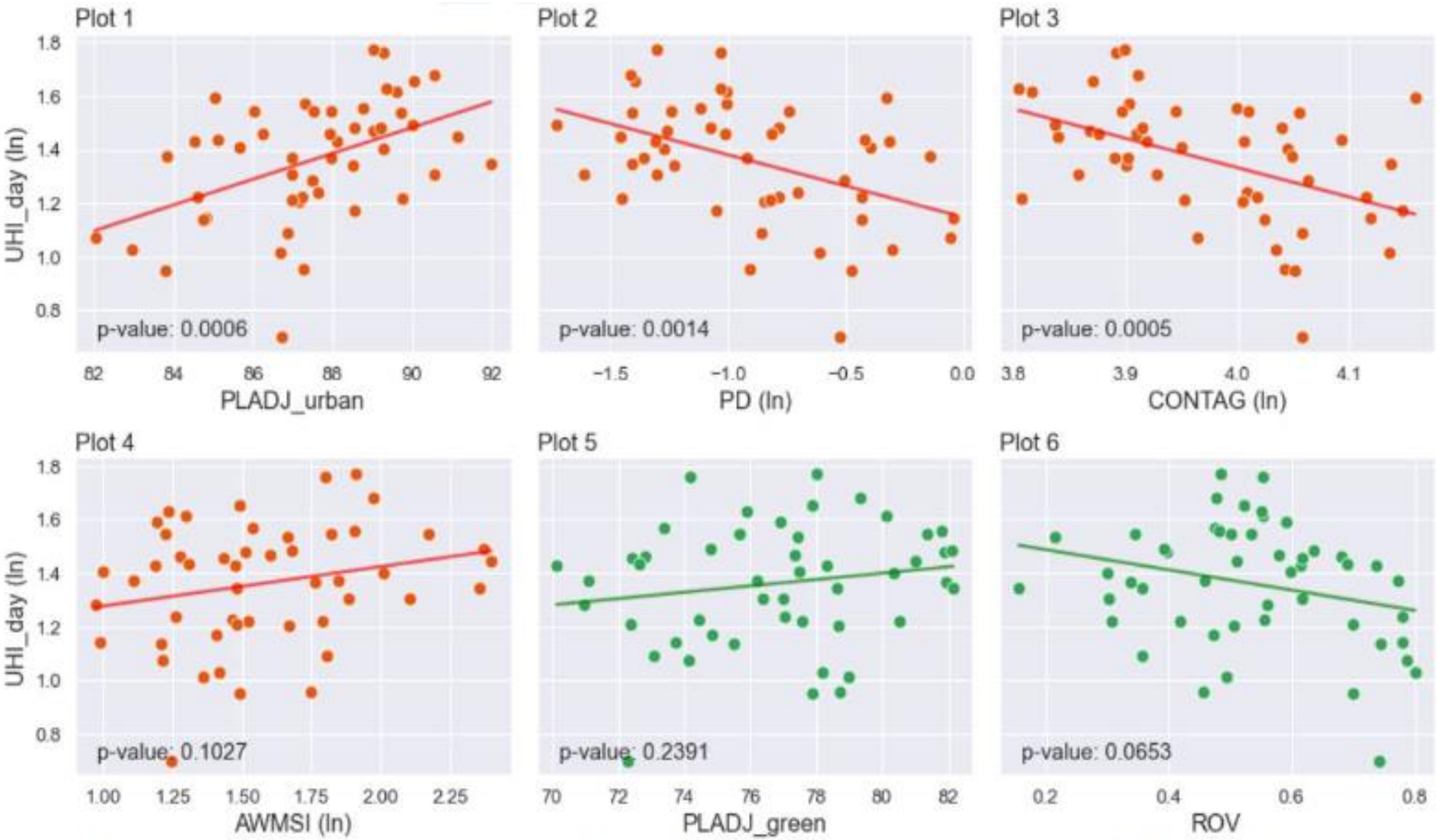


Figure 2: scatterplots and fitted lines presenting the relationships between urban heat island (UHI) effects and landscape metrics.

Appendix

Table 5: Robustness check—regressions investigating the effects of landscape metrics and polycentric development on the day- or night-time UHI effects in 2006.

Panel A: regressions investigate the effects of landscape metrics on the UHI effects

	Models of urban landscape metrics			Models of Greenspace metrics	
	UHI (ln) Day	UHI (ln) Night		UHI (ln) Day	UHI (ln) Night
PLADJ_Urban	.044***	.13***	PLADJ_Green	.001	.021
	(.01)	(.032)		(.005)	(.019)
PD (ln)	-.15***	-.494***	ROV (ln)	-.094*	-.389***
	(.042)	(.114)		(.053)	(.142)
CONTAG (ln)	-.442*	-.393			
	(.254)	(.752)			
AWMSI (ln)	.188***	.61***			
	(.066)	(.169)			

(1) Observations removed due to the extremely low UHI (ln) values: Siegen in daytime models; Siegen and Erfurt in nighttime models. (2) All models include the same control variables as the 2012 models.

Panel B: regressions investigate the effects of polycentric development on the UHI effects.

	Model 1	Model 2	Model 3	Model 4
	UHI (ln) Day	UHI (ln) Day	UHI (ln) Night	UHI (ln) Night
Poly (ln)	-.0745**	.0749	-.1707**	.2177
	(.0327)	(.0708)	(.0773)	(.2539)
Poly (ln)*Medium		-.3		-.5027
		(.2164)		(.4351)
Poly (ln)*Large		-.177**		-.4751*
		(.0834)		(.2632)
Control Variables	Yes	Yes	Yes	Yes
Observations	50	50	48	48
R-squared	.2565	.3115	.306	.3994

(1) Observations removed due to the extremely low UHI (ln) values: Siegen and Erfurt in nighttime models

*Robust standard errors are in parentheses; *** p<.01, ** p<.05, * p<.1*

Polycentric spatial development and policy

- European planning institutions began to promote regional polycentrism in the early 2000s to compete with global cities in North America and Asia (Faludi, 2005).
- The 1999 European Spatial Development Perspective (ESDP):
  - guidance for "sectoral policies with significant spatial impacts"
  - linked polycentric urban forms, economic competitiveness, and deconcentrating economic growth (Commission of the European Communities, 1999: 11).
- A wave of Euro-centric research on polycentricity followed,
  - the connection between polycentric urban form and desirable social, environmental, and economic outcomes (see, among many others, Aguilera, 2005; Kloosterman and Lambregts, 2001; Lambregts, 2009; Meijers and Sandberg, 2006; Meijers 2008; Hall and Pain 2006).

Spatial (landscape) metrics for urban spatial patterns

Table 1: The equation and definition of landscape metrics and polycentricity index

Metric	Equation and definition
Percentage of like adjacencies (PLADJ)	$PLADJ_i = \frac{g_{ii}}{\sum_{k=1}^{m} g_{ik}} * 100$ g_{ii} = number of adjacent pairs of pixels in land-use class i. g_{ik} = number of adjacent pairs of pixels between land-use class i and k. m = number of land-use classes in the landscape.
Patch density (PD)	$PD_i = \frac{n_i}{a_i} * 10000 * 100$ n_i = number of patches in class i. a_i = total area of class i.
Contagion index (CONTAG)	$CONTAG = \{1 + \frac{1}{2ln(m)}[\left(\sum_{i=1}^{m}\sum_{k=1}^{m} p_i \frac{g_{ii}}{\sum_{k=1}^{m} g_{ik}}\right) - lnp_i \frac{g_{ii}}{\sum_{k=1}^{m} g_{ik}}]\} * 100$ g_{ik} = number of adjacent pairs of pixels between class i and k. All pairs of pixels in the adjacency matrix are double counted.
Area-weighted mean shape index (AWMSI)	$AWMSI_i = \sum_{j=1}^{n} [(\frac{0.25 p_{ij}}{\sqrt{a_{ij}}})(\frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}})]$ P_{ij} = perimeter of patch j in class i. a_{ij} = area of patch ij. n = total number of patches in class i.
Ratio of vegetated area (ROV)	$ROG = \frac{a_g}{A}$ a_g = total area of vegetated spaces within a metropolitan area, including urban greenspace, rural shrub, and forest.
Polycentricity index (POLY)	Step1: $P_i(n) = 1 - \frac{\sigma_n}{\sigma_{max}}, (n = 2,3,4)$ Step2: $POLY_i = \frac{P_i(2) + P_i(3) + P_i(4)}{3}$ Step 1: $P_i(n)$ = degree of polycentricity for region i incorporating the top n centers. σ_n = standard deviation of population for the top n centers. σ_{max} = the maximum standard deviation of population of an absolute monocentric two-center scenario, namely one center with zero population and another with the maximum population in the region. Step 2: $POLY_i$ = the average degree of polycentricity considering $P_i(2)$, $P_i(3)$,and $P_i(4)$.