

Relationships between Changes in Urban Characteristics and Air Quality in East Asia from 2000 to 2010

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Supplemental tables include a list of data sources and saturated regression models. Supplemental figures include variance-covariance matrices, compactness index examples, and maps of spatial distributions of several key variables.

Table S1. Data sources and characteristics

	Source	Spatial Resolution	Units
PM_{2.5}	Van Donkelaar et al. ¹⁴	0.1°	µg/m ³
NO₂	Lamsal et al. ¹³	0.1°	ppb
Urban Classification	World Bank	250m	categorical
Population Density	NASA SEDAC	1km	persons*km ⁻¹
NDVI	NASA LP DAAC	250m	Relative scale (-1-1)
Impervious Surface Area	NOAA NGDC	1km	%
Light at Night	NOAA NGDC	30"	%
Rainfall	NASA EOC	0.25°	mm
Temperature	NASA EOC	0.1°	°C

* primary and secondary roads and turnoffs ** tertiary and residential roads and turnoffs ***sum of major and minor density.

Table S2. Non-stratified multivariate linear regression models for change in NO₂ and PM_{2.5}.

	NO ₂		PM _{2.5}	
	Coefficient	Std Error	Coefficient	Std Error
Urban Expansion				
Area (sq km)	1.27x10 ⁻³	2.18x10 ^{-4***}	4.99x10 ⁻⁴	1.13x10 ⁻³
Population (1000s)	-2.42x10 ⁻⁷	5.14x10 ⁻⁷	-5.77x10 ⁻⁷	2.65x10 ⁻⁶
Change in Urban Characteristics				
Compactness Index (0-1)	-2.31	1.10*	-10.08	5.68
Population Density	-1.75x10 ⁻⁵	3.32x10 ⁻⁶	-8.34x10 ⁻⁷	1.71x10 ⁻⁵
NDVI (-1-1)	0.15	9.70x10 ⁻²	-0.49	0.50
Impervious Surface Area (%)	-0.10	1.91x10 ^{-2***}	-0.32	9.84x10 ^{-2**}
Lights at Night (%)	7.99x10 ⁻²	1.98x10 ^{-2***}	0.31	0.10**
Change in Urban Characteristic Heterogeneity				
Population Density	7.61x10 ⁻⁵	2.74x10 ^{-5**}	6.13x10 ⁻⁴	1.41x10 ^{-4***}
NDVI (-1-1)	-0.15	0.28	-1.54	1.46
Impervious Surface Area (%)	3.49x10 ⁻²	2.06x10 ⁻²	0.16	0.11
Lights at Night (%)	-0.11	3.49x10 ^{-2**}	-0.41	0.18*
Baseline (2000) Urban Characteristics				
Area (sq km)	1.45x10 ⁻⁵	5.75x ⁻⁴	4.14x10 ⁻³	3.00x ⁻³
Population (1000s)	-6.17x10 ⁻⁵	1.65x10 ⁻⁴	-4.24x10 ⁻⁴	8.50x10 ⁻⁴
NDVI (-1-1)	6.37x10 ⁻³	5.55x10 ⁻³	5.35x10 ⁻²	2.87x10 ⁻²
Impervious Surface Area (%)	-7.82x10 ⁻²	1.40x10 ^{-2***}	-0.187	7.25x10 ^{-2*}
Lights at Night (%)	4.01x10 ⁻²	1.64x10 ^{-2*}	-9.04x10 ⁻²	8.45x10 ⁻²
Adjustment Factors				
Distance to Coast (km)	-2.11x10 ⁻³	2.762x10 ^{-4***}	-7.78x10 ⁻³	1.43x10 ^{-3***}
Annual Rainfall (mm)	-4.88x10 ⁻²	6.13x10 ^{-3***}	-0.16	3.17x10 ^{-2***}
Annual Temperature (°C)	-2.15x10 ⁻²	6.56x10 ^{-3**}	-0.14	3.39x10 ^{-2**}
Adjusted R²	0.46		0.34	

*p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

Table S3. Associations between NO₂ change and urban expansion and urban characteristics – full model.

	Urban Size								
	100,000-250,000 (n=235)			250,000-1,000,000 (n=340)			> 1,000,000 (n=255)		
	Coefficient	Std Error	R2	Coefficient	Std Error	R2	Coefficient	Std Error	R2
Urban Expansion									
Area (sq km)	2.15x10 ⁻²	7.88x10 ^{-3**}	0.03	1.05x10 ⁻²	2.96x10 ^{-3***}	0.08	1.22x10 ⁻³	2.34x10 ^{-4***}	0.13
Population (1000s)	5.04x10 ⁻³	3.50x10 ⁻³	0.08	-1.11x10 ⁻³	9.91x10 ⁻⁴	0.05	-3.81x10 ⁻⁶	5.61x10 ⁻⁶	0.02
R2			0.11			0.13			0.15
Change in Urban Characteristics									
Compactness Index (0-1)	2.42	1.99	<0.01	-2.34	1.87	<0.01	3.68	2.39	<0.01
Population Density	-1.79x10 ⁻³	1.58x10 ⁻⁴	<0.01	7.75x10 ⁻⁵	6.18x10 ⁻⁵	0.01	1.99x10 ⁻⁶	3.59x10 ⁻⁶	0.01
NDVI (-1-1)	-1.69	1.75	0.04	1.00	1.40	0.02	-1.13x10 ⁻²	2.13	0.04
Impervious Surface Area (%)	-0.16	3.96x10 ^{-2***}	<0.01	-8.71x10 ⁻²	2.68x10 ^{-2**}	0.01	-8.14x10 ⁻²	4.44x10 ⁻²	<0.01
Lights at Night (%)	9.96x10 ⁻²	2.91x10 ^{-2***}	0.05	9.09x10 ⁻²	3.41x10 ^{-2**}	0.05	0.19	5.54x10 ^{-2**}	0.25
R2			0.10			0.10			0.31
Change in Urban Characteristic Heterogeneity									
Population Density	-6.71x10 ⁻⁵	5.19x10 ⁻⁵	0.02	1.46x10 ⁻⁴	6.10x10 ^{-5*}	0.03	9.04x10 ⁻⁵	5.80x10 ⁻⁵	0.06
NDVI (-1-1)	-3.80	5.28	<0.01	-0.87	4.17	<0.01	-5.30	6.04	0.02
Impervious Surface Area (%)	1.86x10 ⁻²	3.22x10 ⁻²	0.01	6.13x10 ⁻²	3.13x10 ⁻²	0.07	-6.35x10 ⁻²	6.05x10 ⁻²	0.02
Lights at Night (%)	-5.96x10 ⁻²	5.56x10 ⁻²	0.01	-8.75x10 ⁻²	5.91x10 ⁻²	0.02	-6.26x10 ⁻²	7.33x10 ⁻²	0.02
R2			0.04			0.13			0.12
Baseline (2000) Urban Characteristics									
Area (sq km)	-1.28x10 ⁻²	3.70x ^{-3**}	0.03	1.79x10 ⁻³	2.29x10 ⁻³	0.01	-3.69x10 ⁻⁴	6.84x10 ⁻⁴	<0.01
Population (1000s)	3.00x10 ⁻³	3.81x10 ⁻³	<0.01	-5.76x10 ⁻⁴	1.12x10 ⁻³	0.01	8.94x10 ⁻⁴	2.08x10 ⁻³	<0.01
NDVI (-1-1)	-2.62x10 ²	81.48**	0<0.01	-2.22	84.63	0.02	-1.06x10 ⁻²	1.62x10 ⁻²	0.07
Impervious Surface Area (%)	-0.15	2.61x10 ^{-2***}	0.06	-4.42x10 ⁻²	2.32x10 ⁻²	<0.01	-9.47x10 ⁻²	3.56x10 ^{-2**}	0.02
Lights at Night (%)	7.03x10 ⁻²	2.53x10 ^{-2**}	0.05	4.04x10 ⁻²	2.55x10 ⁻²	0.01	8.87x10 ⁻²	4.69x10 ⁻²	0.01
R2			0.14			0.04			0.10
Adjustment Factors									
Distance to Coast (km)	-2.56x10 ⁻³	4.81x10 ^{-4***}	0.04	-1.71x10 ⁻³	3.73x10 ^{-4***}	0.04	-1.72x10 ⁻³	6.38x10 ^{-4**}	0.02
Annual Rainfall (mm)	-4.96x10 ⁻²	9.82x10 ^{-3***}	0.07	-3.76x10 ⁻²	8.94x10 ^{-3***}	0.05	-3.70x10 ⁻²	1.68x10 ^{-2*}	0.03
Annual Temperature (°C)	-3.14x10 ⁻²	1.03x10 ^{-2**}	0.02	-1.19x10 ⁻²	1.03x10 ⁻²	<0.01	-4.30x10 ⁻²	1.67x10 ^{-2*}	0.02
R2			0.12			0.09			0.07
Full Model R2			0.51			0.49			0.75

*p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

Table S4. Multivariate associations between PM_{2.5} change and urban expansion and urban characteristics – full model.

	Urban Size								
	100,000-250,000 (n=235)			250,000-1,000,000 (n=340)			> 1,000,000 (n=255)		
	Coefficient	Std Error	R2	Coefficient	Std Error	R2	Coefficient	Std Error	R2
Urban Expansion									
Area (sq km)	2.33x10 ⁻⁴	4.29x10 ⁻²	<0.01	3.16x10 ⁻²	1.65x10 ⁻²	0.02	1.09x10 ⁻³	1.22x10 ⁻³	<0.01
Population (1000s)	2.90x10 ⁻²	1.90x10 ⁻²	0.10	-2.81x10 ⁻³	5.52x10 ⁻³	0.09	-5.85x10 ⁻⁷	2.94x10 ⁻⁵	0.01
R2			0.11			0.10			0.02
Change in Urban Characteristics									
Compactness Index (0-1)	-9.03	10.81	<0.01	-3.36	10.40	<0.01	21.80	12.53	0.01
Population Density	-9.30x10 ⁻⁴	8.57x10 ⁻⁴	<0.01	4.17x10 ⁻⁴	3.44x10 ⁻⁴	<0.01	-3.62x10 ⁻⁶	1.88x10 ⁻⁵	0.02
NDVI (-1-1)	-18.28	9.545	0.04	-1.265	7.790	<0.01	6.21	11.15	0.02
Impervious Surface Area (%)	-0.45*	0.22	<0.01	-0.17	0.15	0.01	-0.40	0.23	<0.01
Lights at Night (%)	0.4.0*	0.16	0.08	0.19	0.19	0.09	0.88	0.29**	0.22
R2			0.13			0.10			0.27
Change in Urban Characteristic Heterogeneity									
Population Density	1.19x10 ⁻⁴	2.83x10 ⁻⁴	<0.01	1.41x10 ^{-3***}	3.40x10 ⁻⁴	0.05	4.54x10 ⁻⁴	3.04x10 ⁻⁴	0.05
NDVI (-1-1)	-48.26	28.75	0.01	5.46	23.22	<0.01	-27.86	31.59	0.03
Impervious Surface Area (%)	0.13	0.18	<0.01	0.37*	0.17	0.04	-0.15	0.32	<0.01
Lights at Night (%)	-0.2.8	0.31	<0.01	-0.42	0.33	<0.01	0.31	0.39	<0.01
R2			0.01			0.10			0.08
Baseline (2000) Urban Characteristics									
Area (sq km)	-4.03x10 ⁻³	2.35x10 ⁻²	<0.01	1.33x10 ⁻²	1.27x10 ⁻²	0.01	5.55x10 ⁻³	3.58x10 ⁻³	0.02
Population (1000s)	-1.57x10 ⁻²	2.076x10 ⁻²	0.01	-8.38x10 ⁻³	6.22x10 ⁻³	0.01	-8.26x10 ⁻⁷	1.09x10 ⁻⁶	<0.01
NDVI (-1-1)	1.31x10 ³	4.44x10 ^{2*}	0.01	-1.13x10 ²	4.71x10 ²	<0.01	7.60x10 ²	8.48x10 ²	0.05
Impervious Surface Area (%)	-0.40	1.420x10 ^{-1*}	0.04	4.13x10 ⁻²	0.13	<0.01	-0.19	0.19	<0.01
Lights at Night (%)	4.16x10 ⁻²	1.375x10 ⁻¹	<0.01	-0.28***	0.14	0.01	0.35	0.25	0.01
R2			0.06			0.04			0.08
Adjustment Factors									
Distance to Coast (km)	-6.48x10 ⁻³	2.62x10 ^{-3*}	0.01	-7.81x10 ^{-3*}	2.07x10 ⁻³	0.05	-9.03x10 ⁻³	3.34x10 ^{-3**}	0.04
Annual Rainfall (mm)	-0.14	5.35x10 ^{-2*}	0.02	-4.15x10 ⁻²	4.97x10 ⁻²	<0.01	-0.28	8.77x10 ^{-2**}	0.08
Annual Temperature (°C)	-0.11	5.59x10 ^{-2*}	0.01	-6.36x10 ⁻²	5.75x10 ⁻²	<0.01	-0.17	8.76x10 ⁻²	0.02
R2			0.05			0.06			0.14
Full Model R2			0.36			0.39			0.59

*p-value < 0.05, ** p-value < 0.01, *** p-value < 0.001

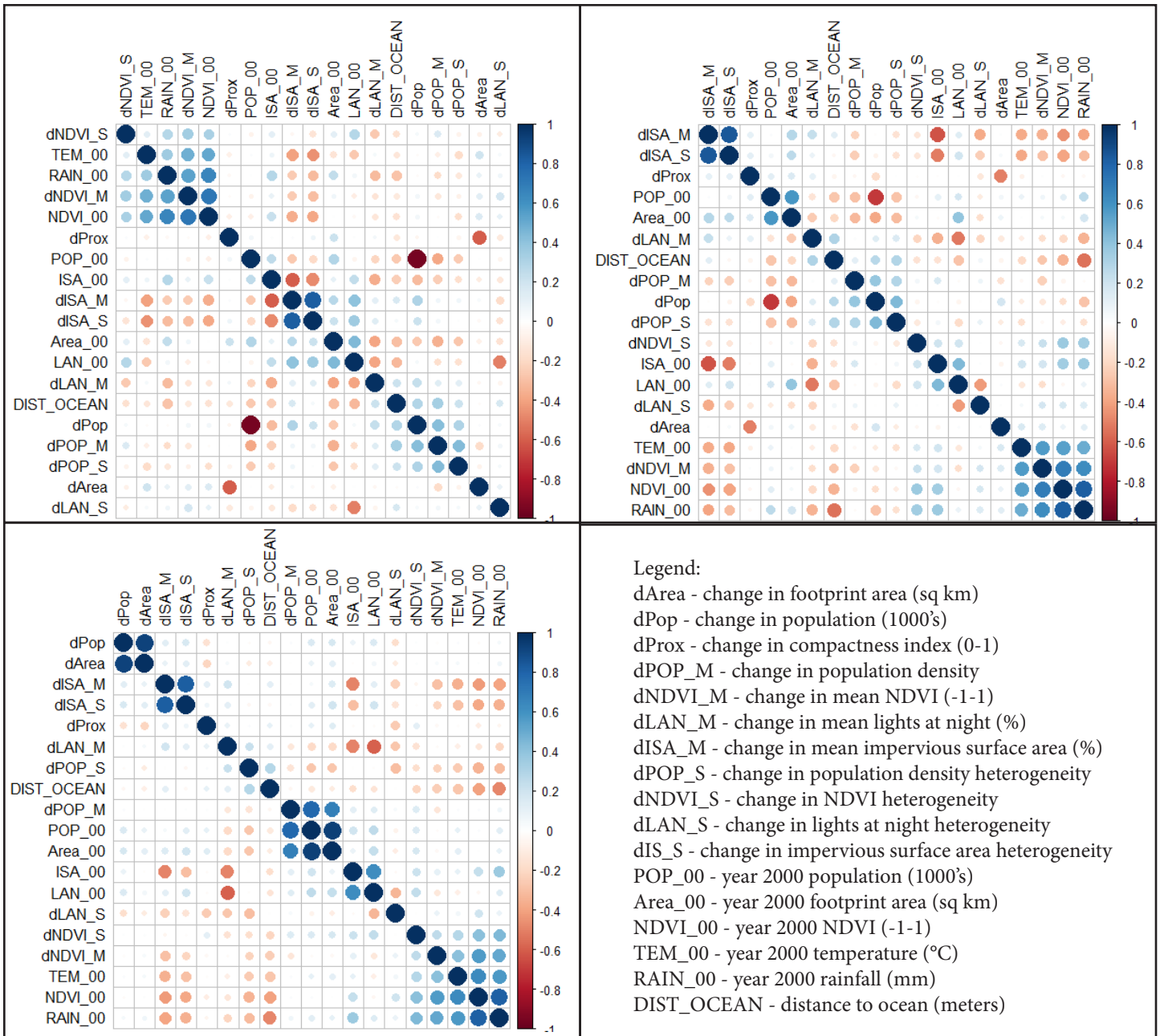


Figure S1. Covariate correlation plots for small (top left), medium, (top right), and large (bottom left) urban areas in East Asia. Variables are organized by hierarchical clustering (“hclust”, R corrrplot package). Year 2000 NDVI, temperature, rainfall, and change in mean NDVI are strongly positively correlated for all city sizes, as are change in mean impervious surface area and change in surface area heterogeneity. The majority of remaining covariate correlations are either similar between small and medium sized cities (e.g. negative correlation between year 2000 population and change in population density) or between medium and large cities (e.g. positive correlation between year 2000 population and year 2000 area), but are not shared across all city sizes, demonstrating changes in urban typologies as urban footprints grow.

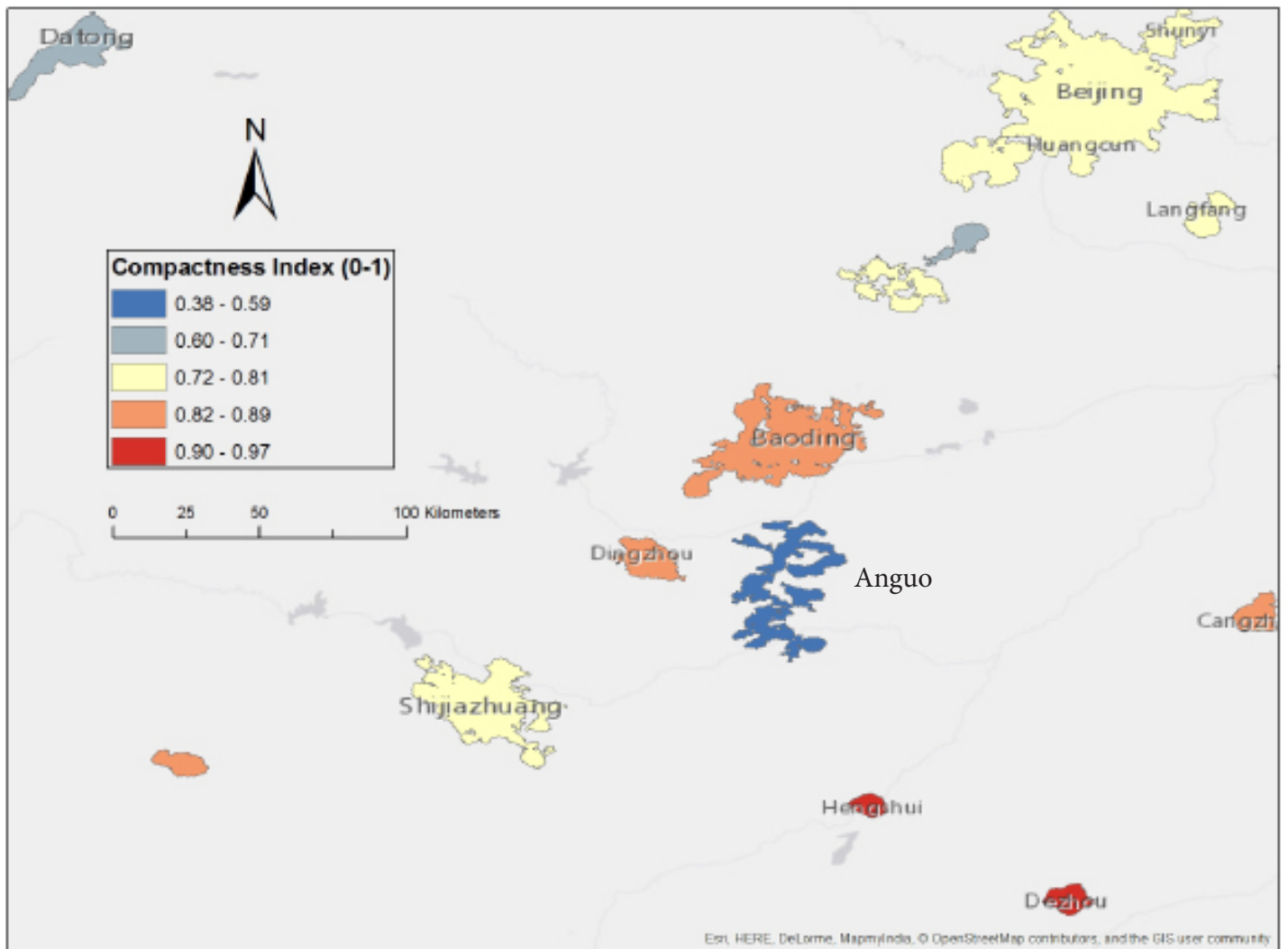


Figure S2. Examples of Compactness Index variation in China. Compactness Index is a measure of the urban sprawl or extent to which a city encroaches on neighboring unurbanized land. Urban areas with a high compactness scores (e.g. Dehzou, China, colored in red in the bottom right) are spherically shaped and tightly centered around the city centroid. Urban areas with low compactness scores (e.g. Anguo, China, colored in blue in the center) have extensive urban sprawl, with a poorly defined city centroid.

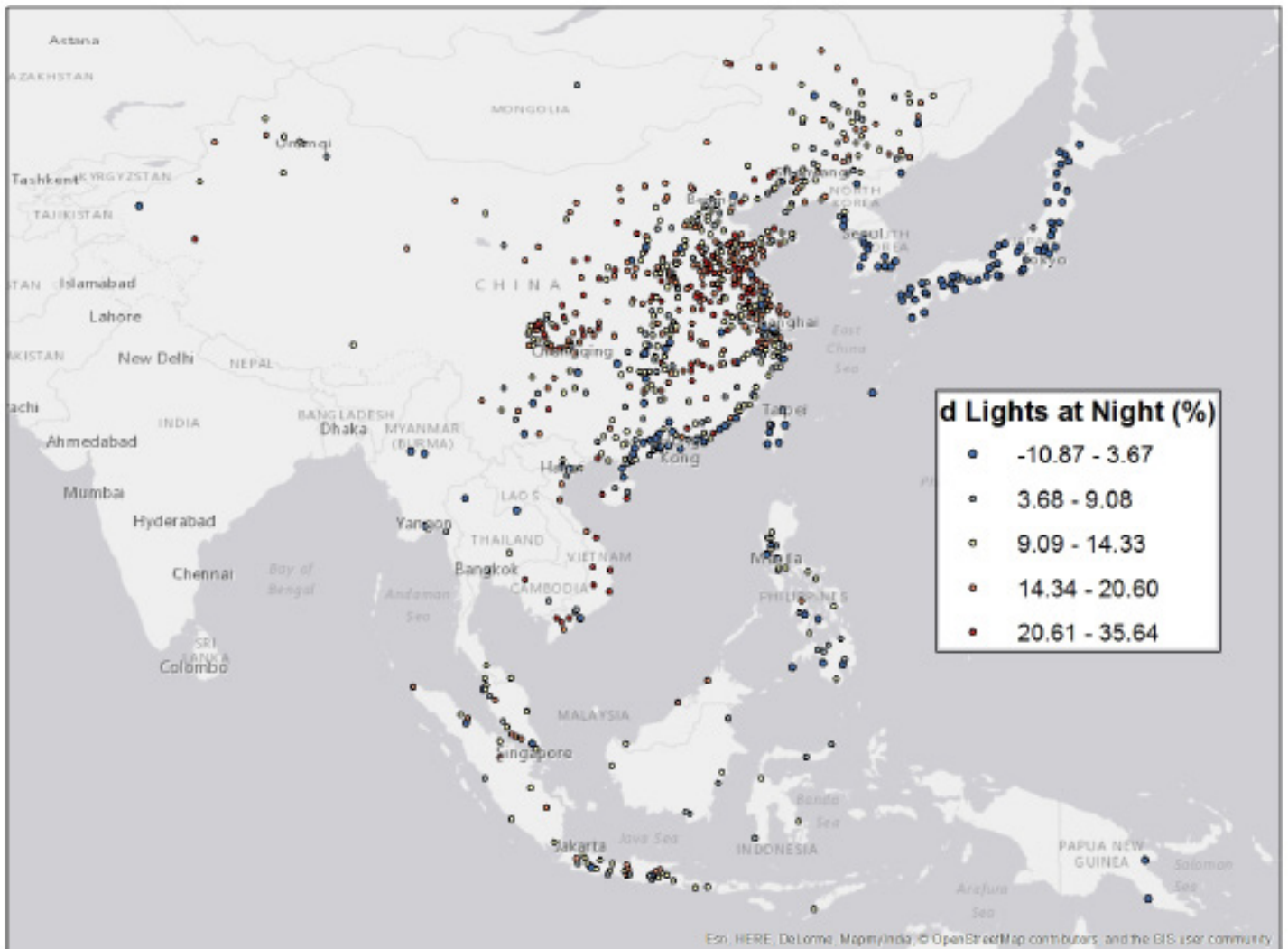


Figure S3. Change in Percent Lights at Night from 2000 - 2010, grouped by quintile, for 830 Cities in Eastern Asia. Reductions were greatest in Japan, South Korea, and Hong Kong, while increases were greatest in Northeastern China.

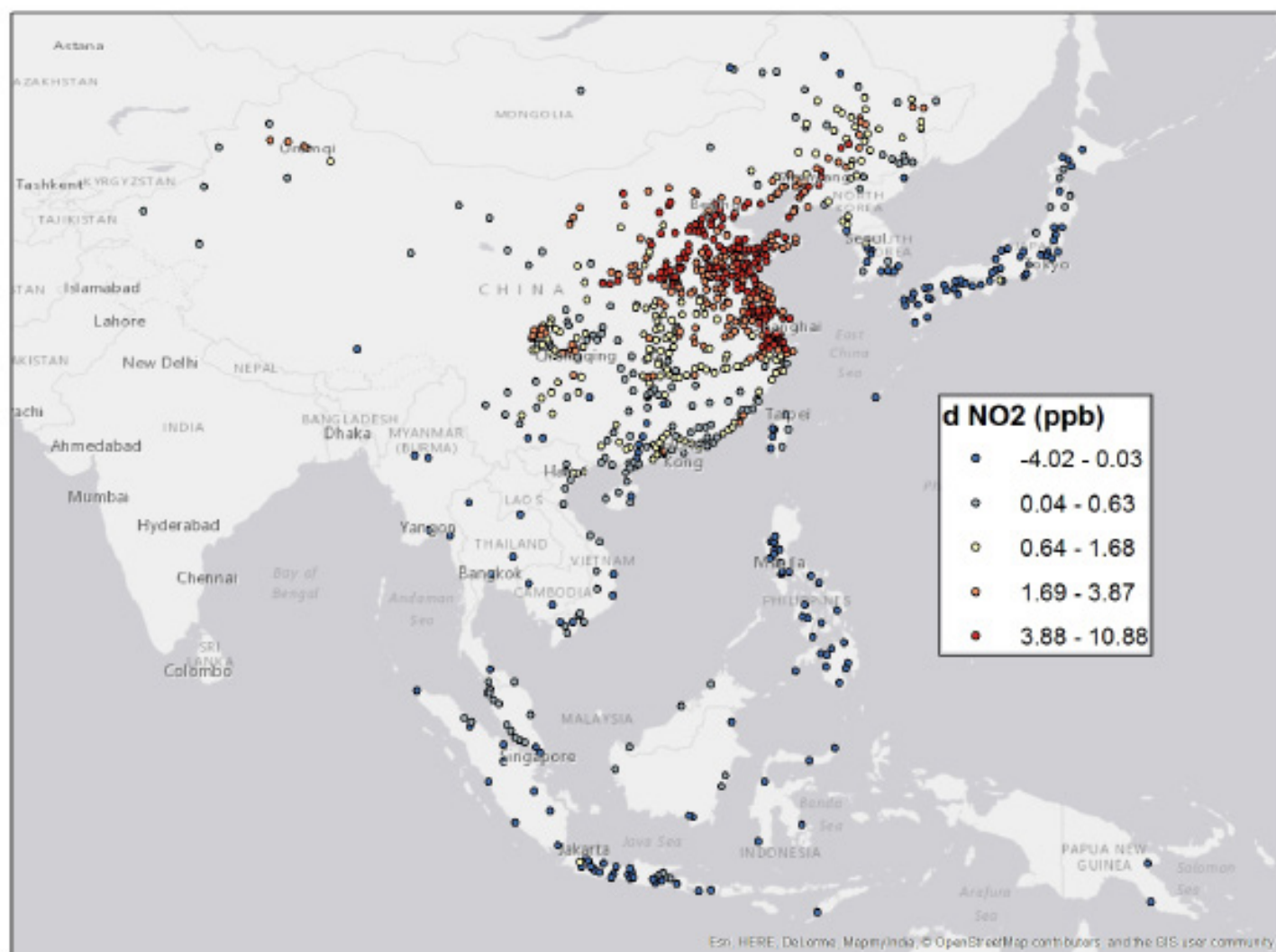


Figure S4. Change in NO₂ from 2000 - 2010, grouped by quintile, for 830 Cities in Eastern Asia. Reductions were greatest in Japan, the Philippines, and Singapore, while increases were greatest in Northeastern China.

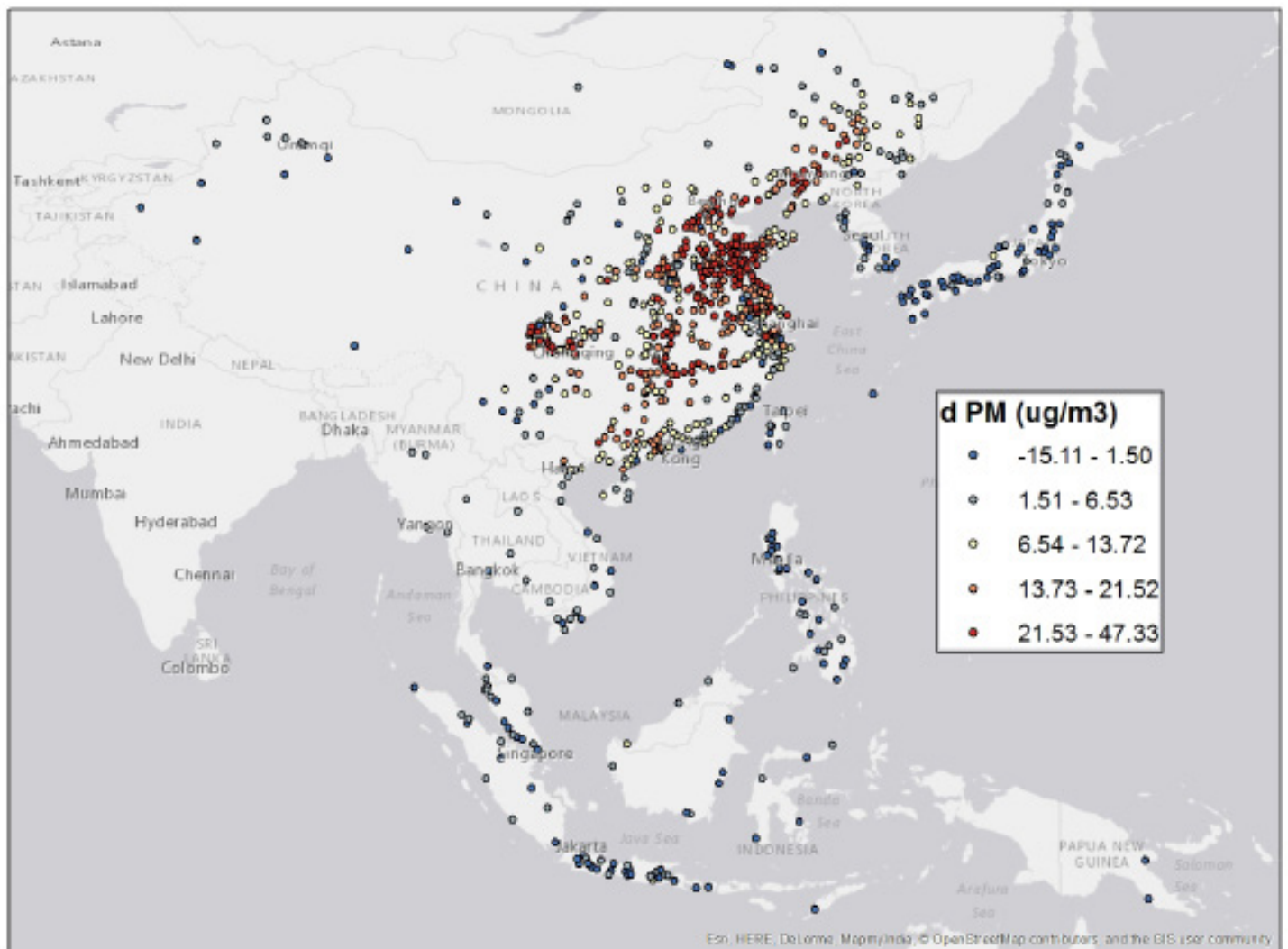


Figure S5. Change in PM_{2.5} from 2000 - 2010, Grouped by Quintile, for 830 Cities in Eastern Asia. Reductions were greatest in Japan, South Korea, and Hong Kong, while increases were greatest in Northeastern and Central China.

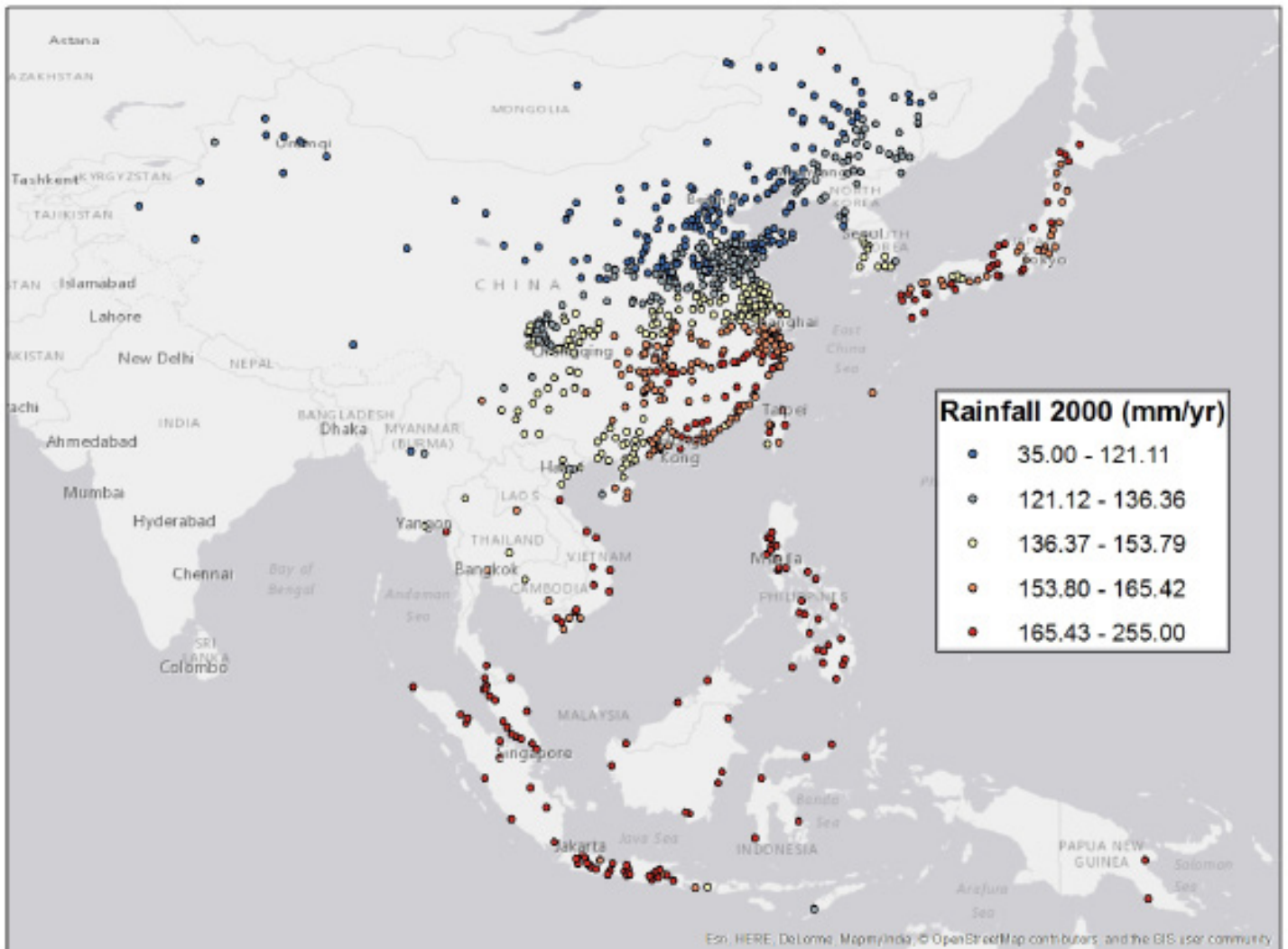


Figure S6. Year 2010 Average Annual Rainfall, Grouped by Quintile, for 830 Cities in Eastern Asia. Rainfall levels are spatially clustered.