Uncharted Waters: Effects of Maritime Emission Regulation

Jamie Hansen-Lewis and Michelle Marcus

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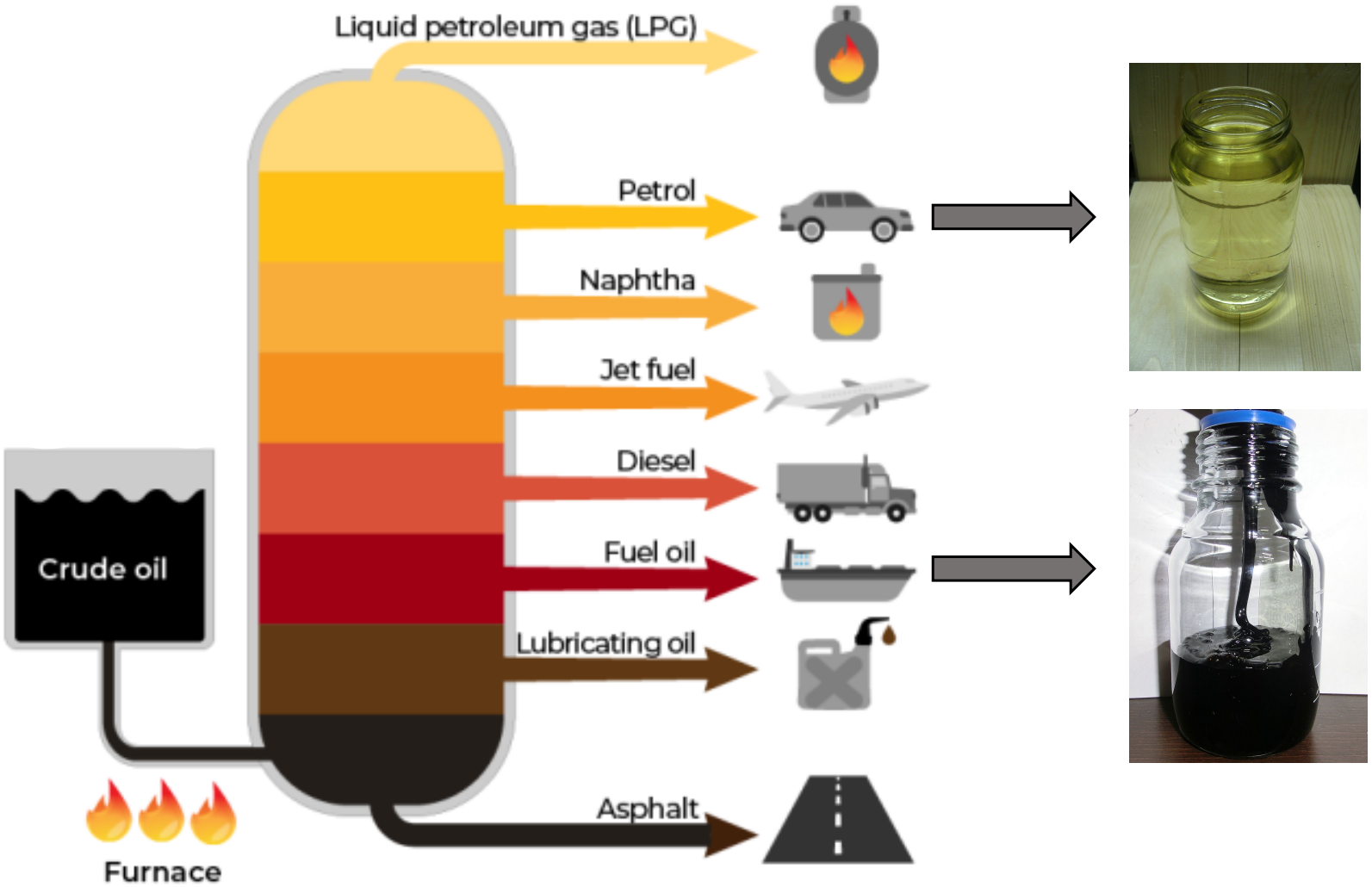
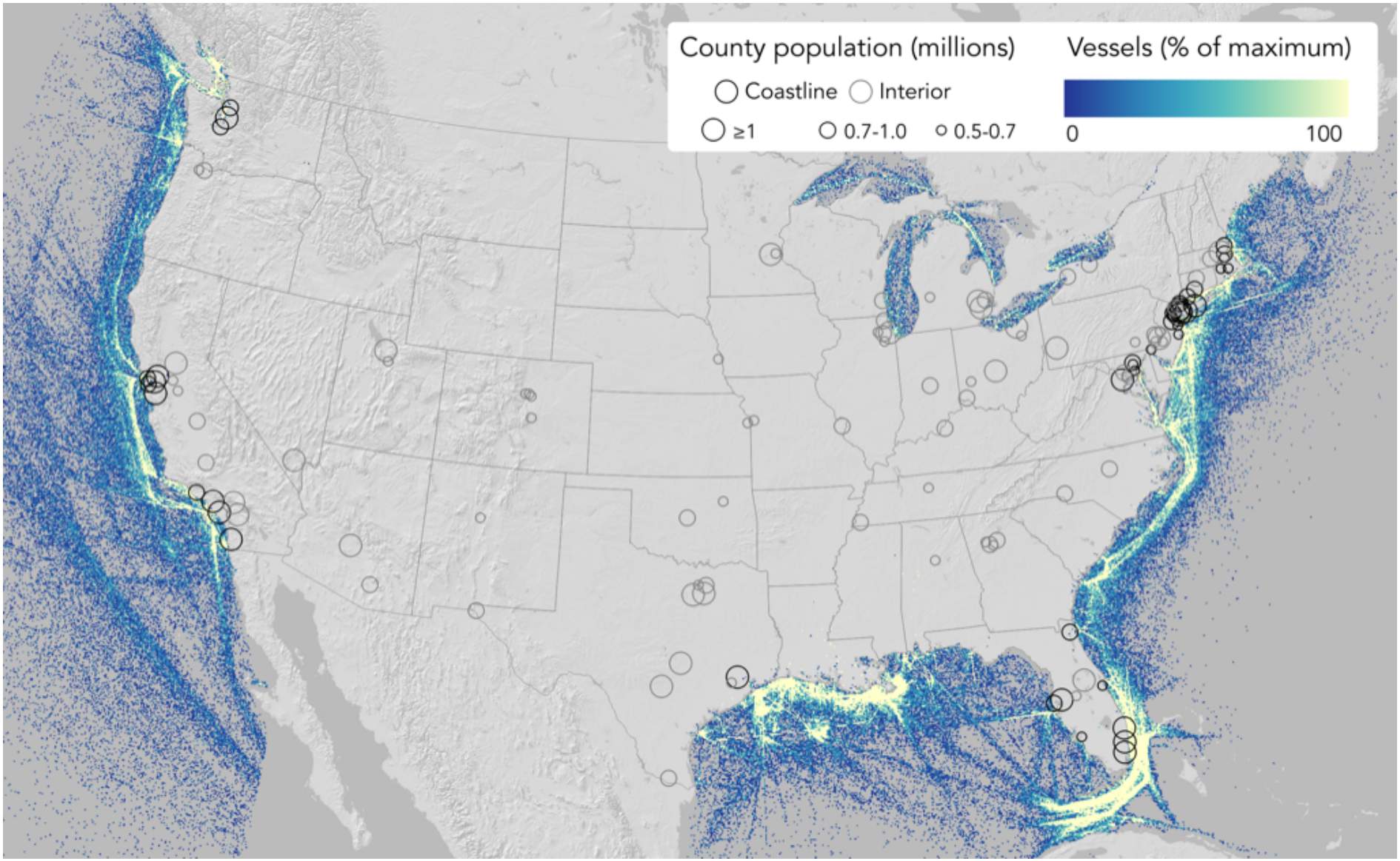
Marine fuels pollute more than car fuels



Maritime emissions are near people



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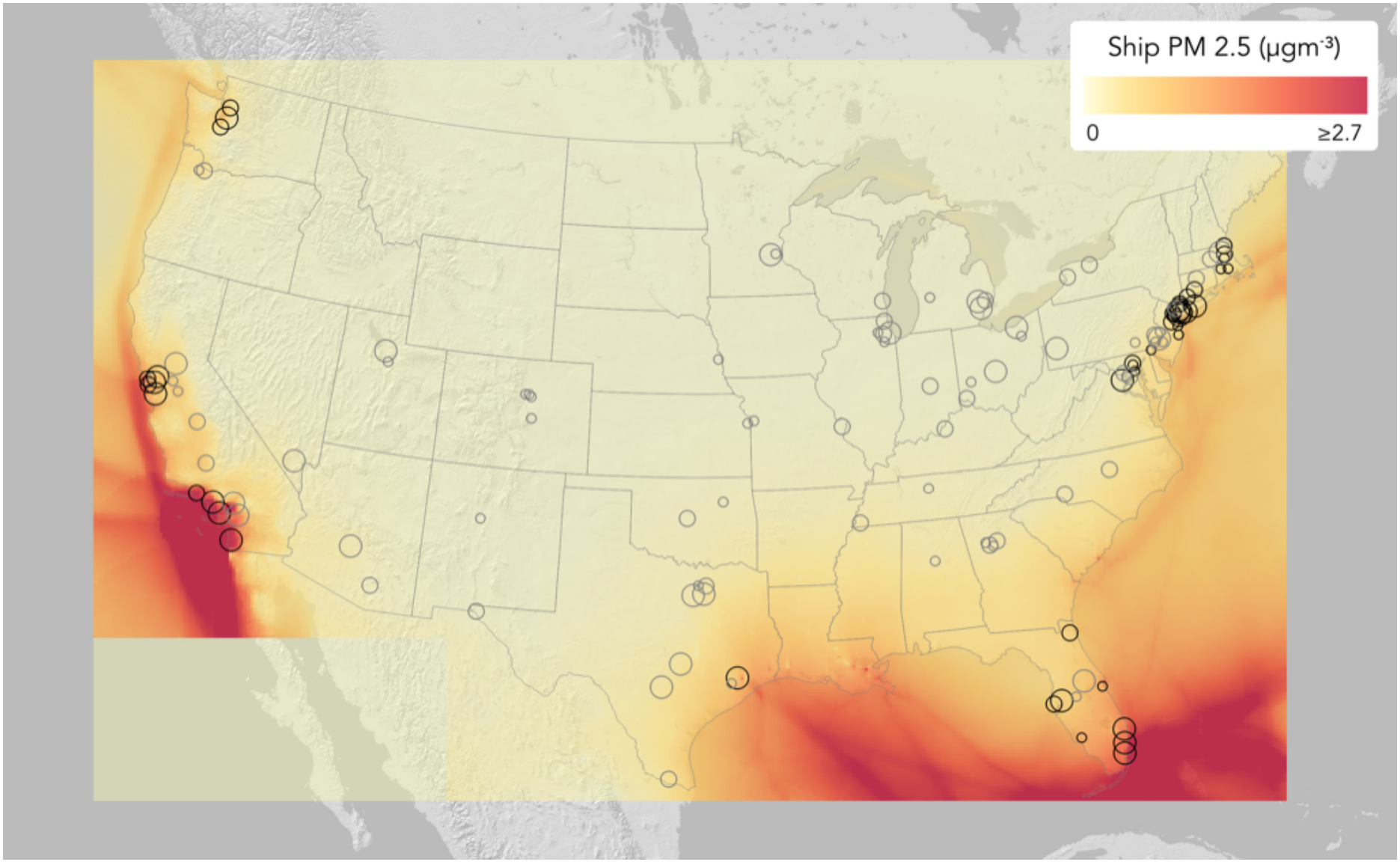
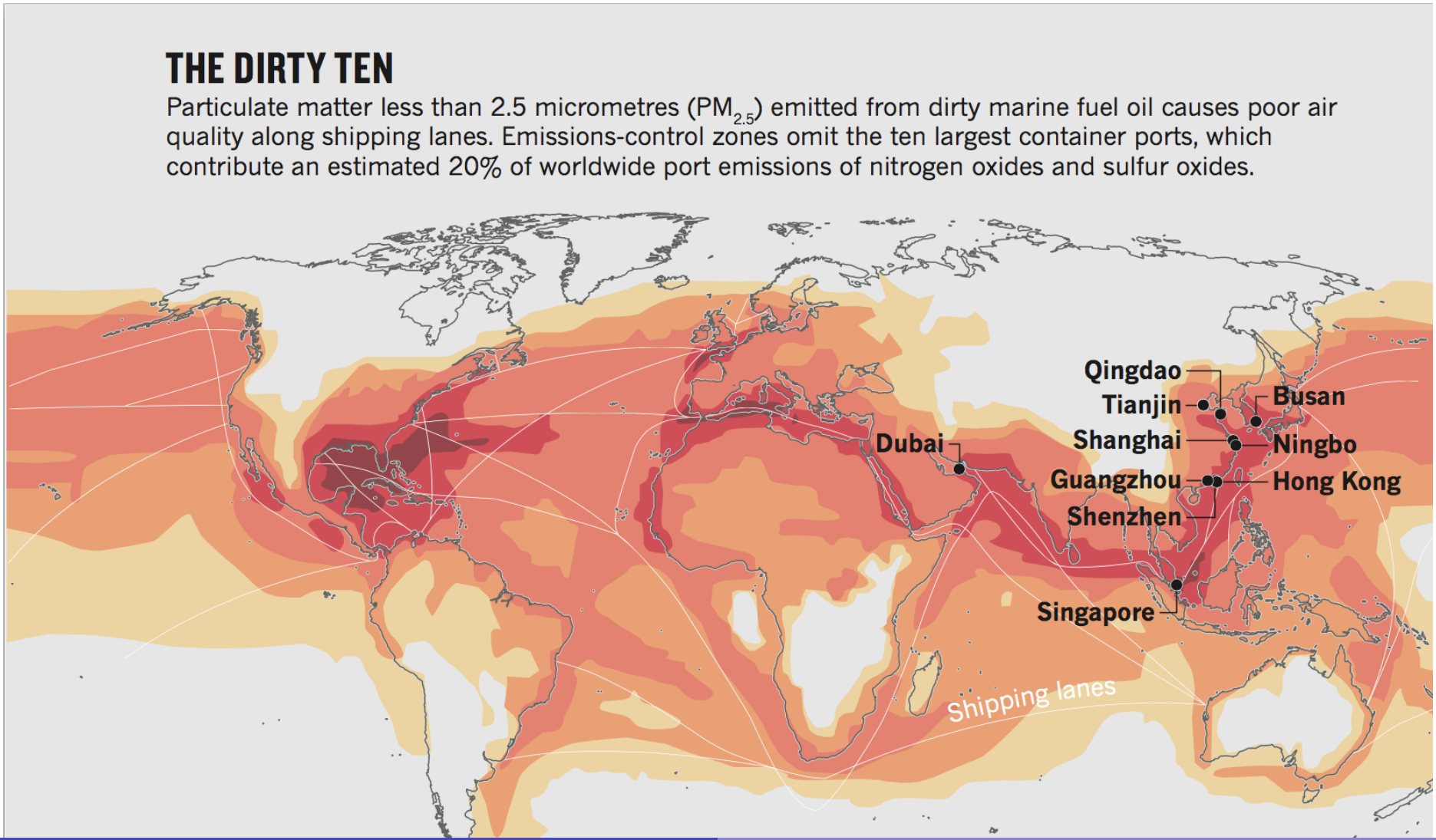


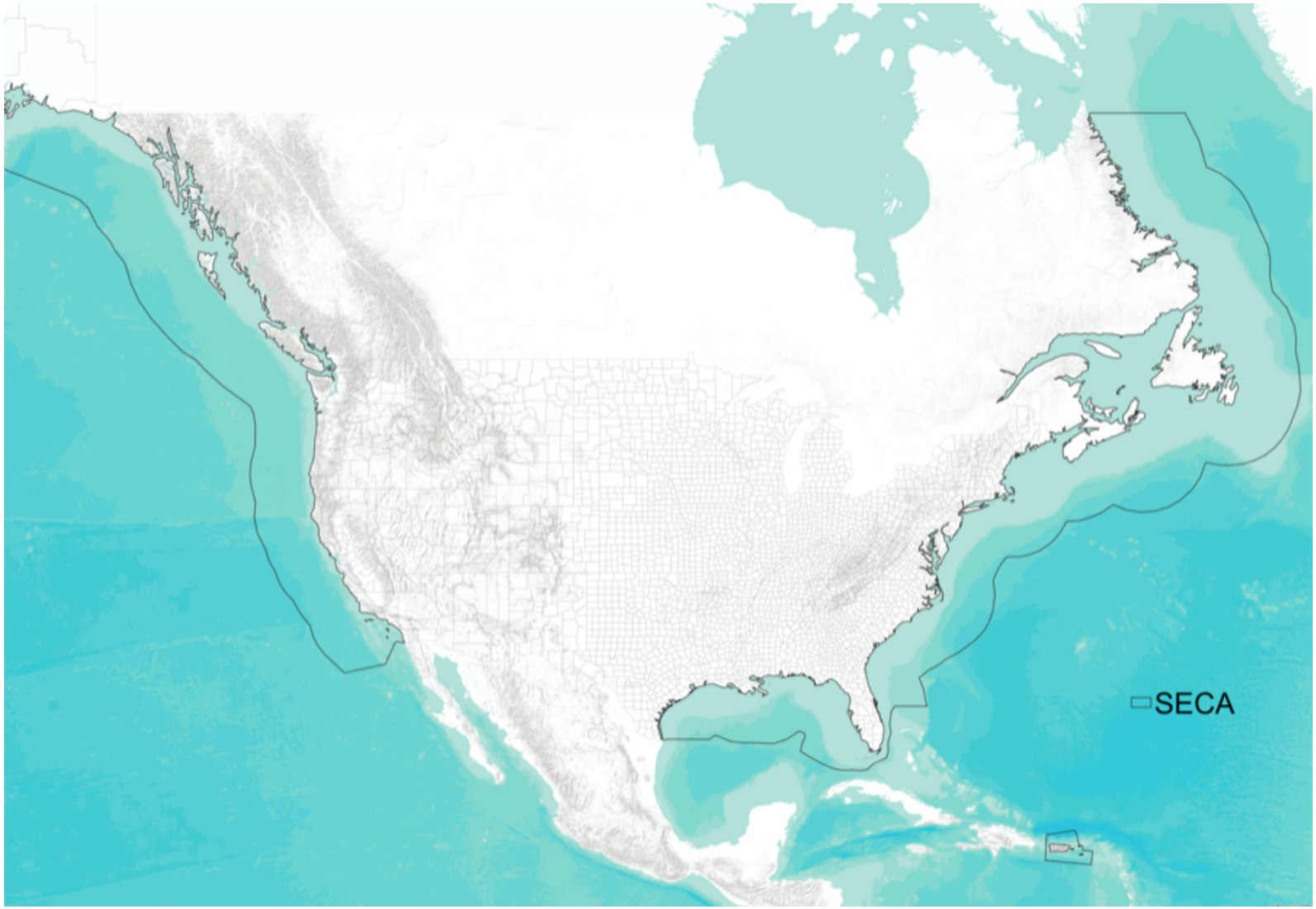
PM2.5 ≈ half world's cars



How do maritime emissions affect PM2.5 and health?

- **Context:** "Emissions Control Area" low sulfur fuel required within 200 nm of US coastline starting in 2012.

Emissions Control Area (ECA)



timeline ca

How do maritime emissions affect PM2.5 and health?

- **Context:** "Emissions Control Area" low sulfur fuel required within 200 nm of US coastline starting in 2012.
  - Substantial compliance costs. Fuel $\approx$ 75% of operating costs; low sulfur fuel $\approx$ 30-50% more expensive.
  - Lack of ex-post evaluation.

How do maritime emissions affect PM2.5 and health?

- **Context:** "Emissions Control Area" low sulfur fuel required within 200 nm of US coastline starting in 2012.
  - Substantial compliance costs. Fuel $\approx$ 75% of operating costs; low sulfur fuel $\approx$ 30-50% more expensive.
  - Lack of ex-post evaluation.
- **Approach:** Estimate ECA effect on PM2.5, infant health, and mortality.
  - Intensity = ex-ante estimates of policy's effect on PM2.5

Our contributions

1. First ex-post evaluation of US ECA implementation, a major and controversial environmental policy.
   - PM2.5 declined 4%, low birth weight 1.7%, infant death 2.8%
   - 1/6 the effect of 1970 CAA and 6x effect of cheating diesel emissions
2. Relate and test equivalence of ex-ante and ex-post policy evaluations.
   - Improved precision by using an atmospheric aerosol transportation model to measure exposure
   - 53% of ex-ante forecast was realized
   - Behavioral adaptations muted policy impact: ship operators, other industry, and individuals
3. Estimate relationship between air pollution and health in a new setting.
   - Different exposed population than ports, land-based sources
   - Effect of PM2.5 on infant health is slightly smaller than other settings

Outline

1. Data & Methods

2. Results
   - Air Pollution
   - Health

3. Behavioral Responses
   - Ships
   - Other Industry
   - Individuals

4. Comparing ship emissions to other sources
   - Describing exposure
   - Comparing magnitudes

5. Discussion & Conclusion

Outline

Data: county-month panel

Air quality

- US EPA CMAQ analysis of ECA policy: change in PM2.5 under ECA policy
- US EPA Monitors: monthly mean PM2.5

Weather

- PRISM data: max & min temperature, precipitation.

Infant health & Mortality

- NCHS Vital Statistics Natality and Mortality records: 2006-2016

Outdoor Recreation & Time Use

- American Time Use Survey (ATUS): 2008-2016 ▸ map
- Campsite reservations from Reservations.gov: 2008-2016 ▸ map

How are CMAQ predictions, e_i, created?

For the business as usual (BAU) scenario:

1. Inventory of projected 2020 emissions from (i) maritime shipping and (ii) other sources
2. Emissions dispersion modeled with CMAQ. Model includes:
   - Historical baseline of weather
   - Chemical interactions in atmosphere
3. Annual mean PM2.5 post-dispersion recorded for each 10km pixel

For the ECA scenario:

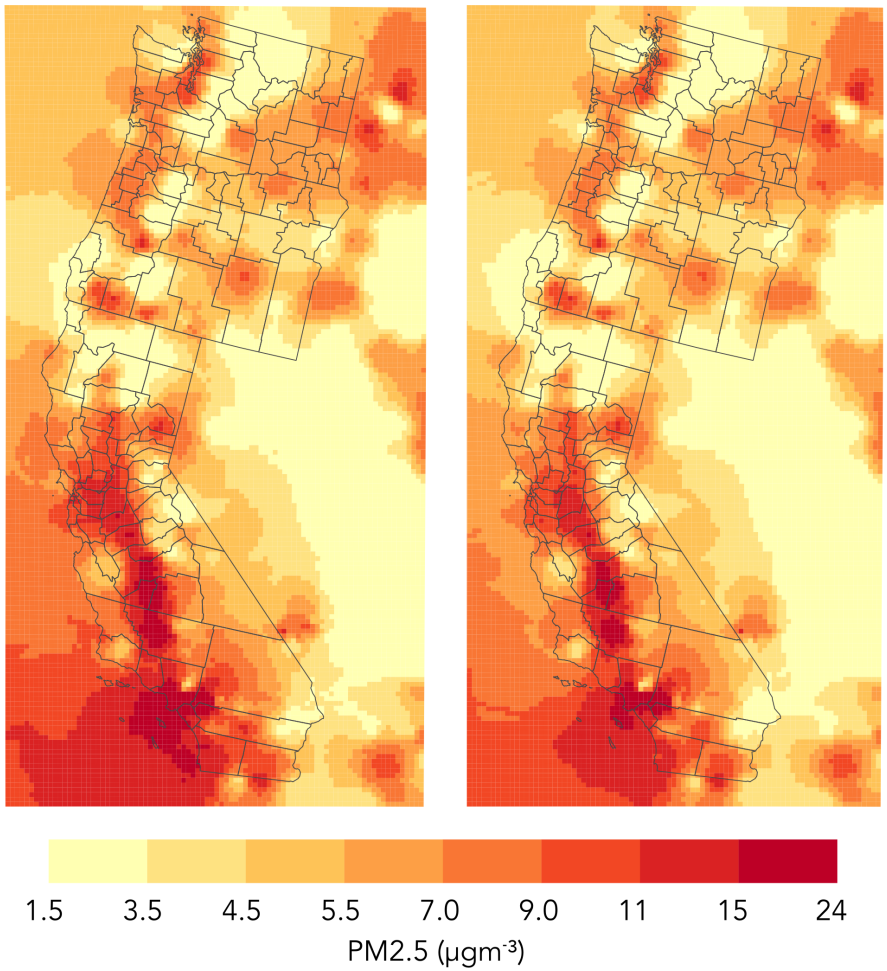
1. Inventory from maritime shipping reduced to level of compliance with policy, other sources same as BAU

Define treatment with regulator's forecast

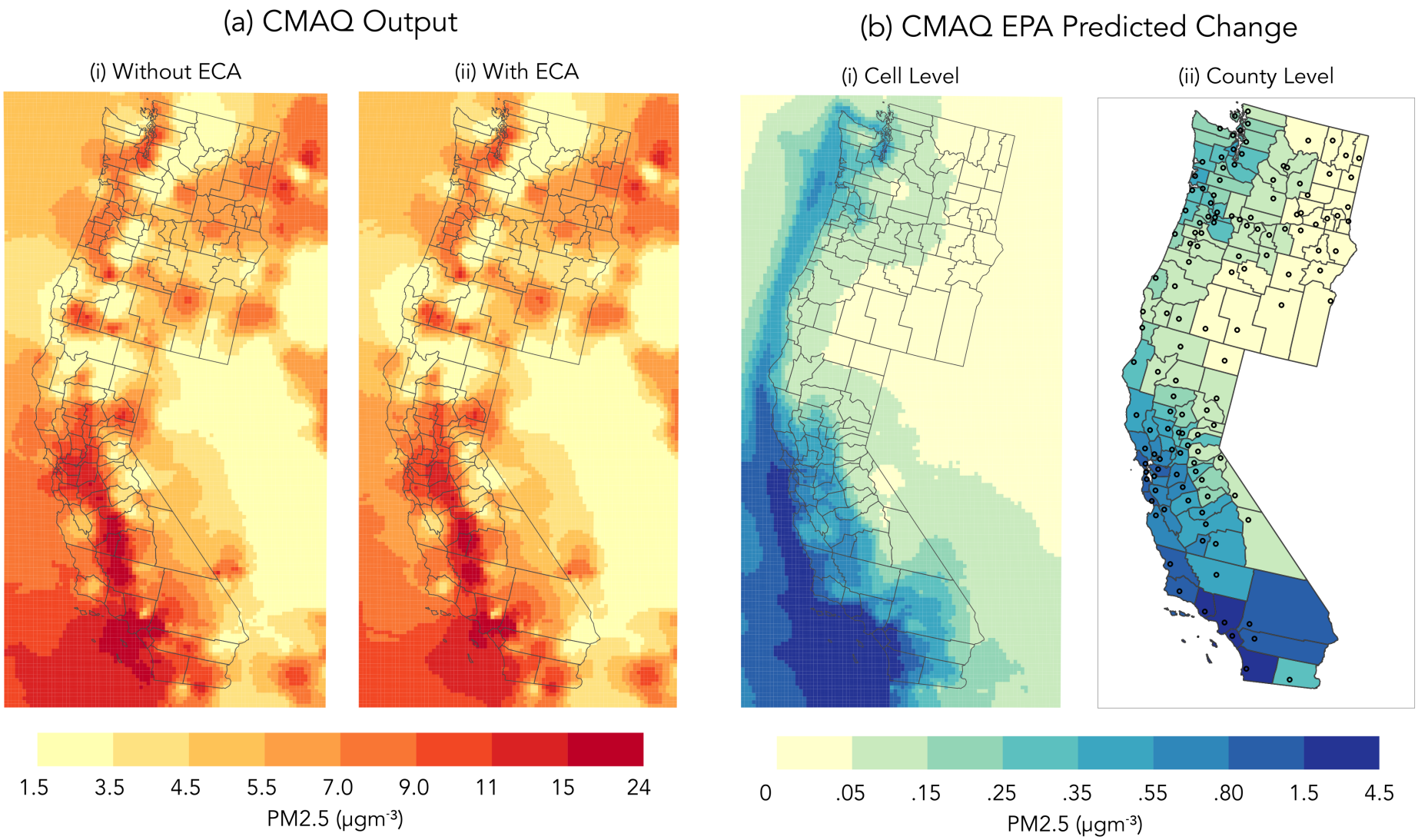
(a) CMAQ Output

(i) Without ECA

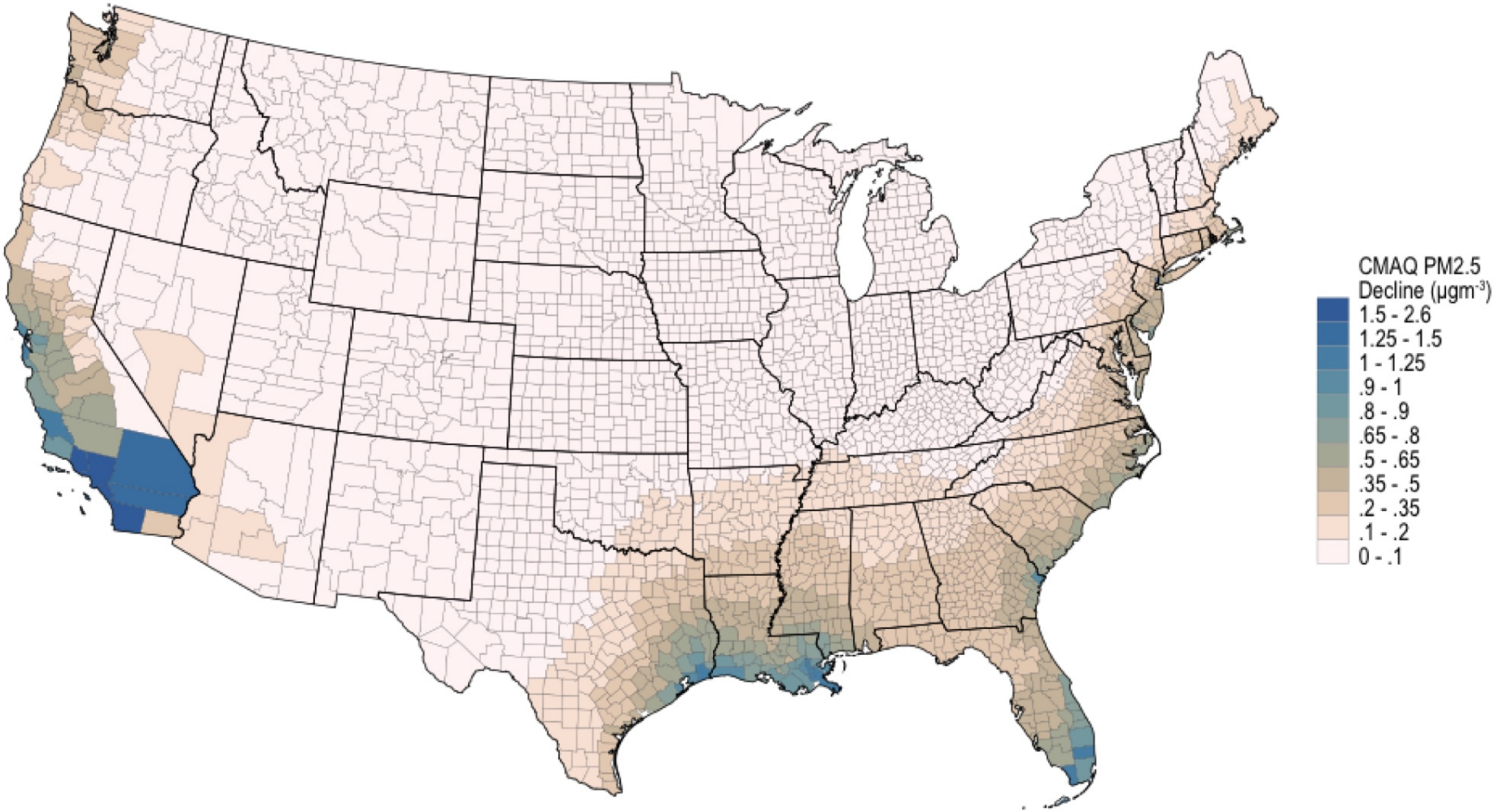
(ii) With ECA



Define treatment with regulator's forecast



CMAQ Predicted Decline in PM2.5



Estimation

$$y_{imy} = \beta postECA_y \times CMAQ_i + \delta X_{imy} + \tau_{ry} + \alpha_{is} + \epsilon_{imy} \quad (1)$$

- outcome y in county i in month-year my
- CMAQ predicted improvement: $CMAQ_i$
- Region-by-year and county-by-season fixed effects: τ_{ry} and α_{is}
- X: Additional controls for weather, employment, and maternal/child characteristics for health regressions
- Weights: number of births conceived (birth outcomes) or by age-specific county population (mortality outcomes)

Outline

Figure: **Effects of ECA on Air Quality**

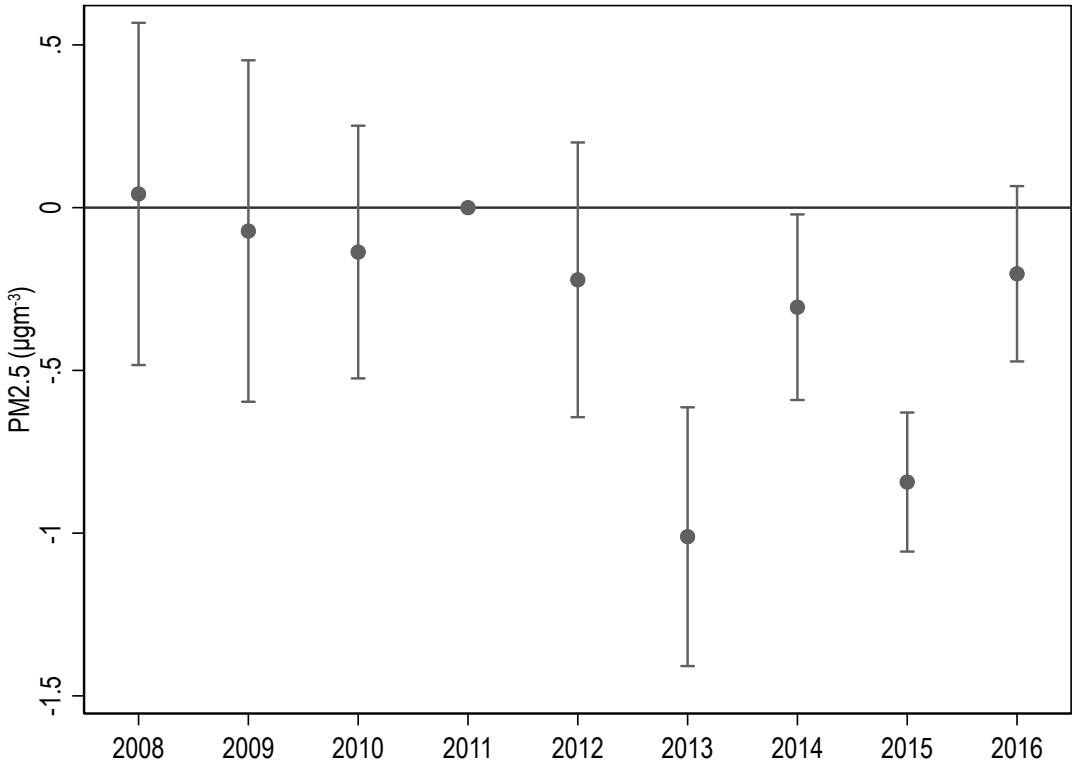
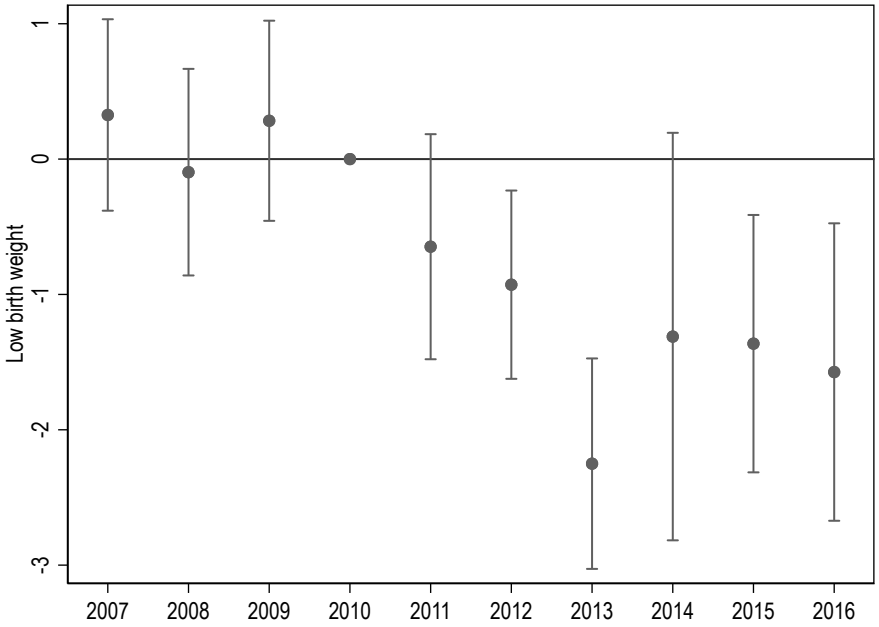


Table: **Effects of ECA on Air Quality and Demographic Characteristics**

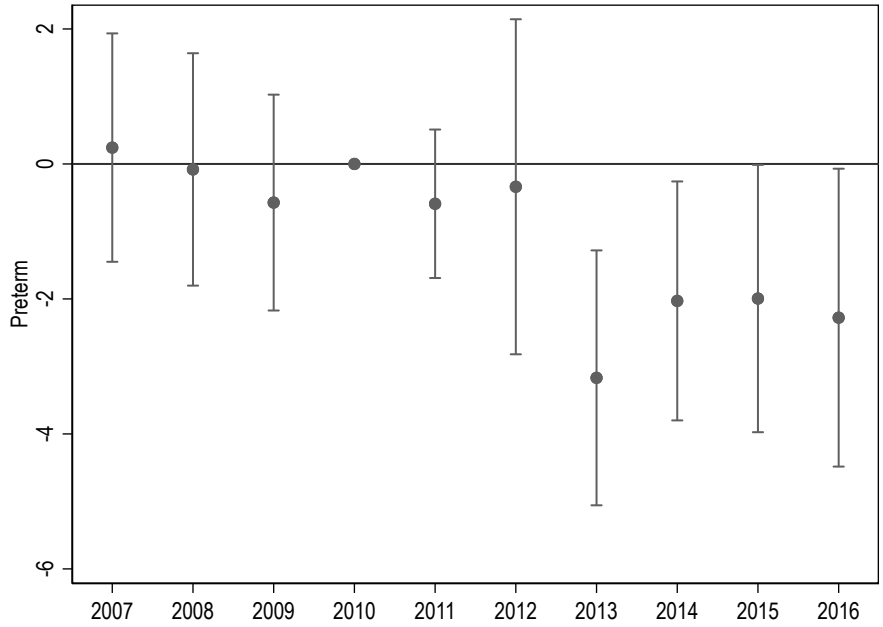
	(1) PM2.5	(2) Demographic index	(3) N conceptions	(4) Unemp. rate
Post-ECA*CMAQ	-0.532	0.879	-54.121	-0.108
	(0.096)***	(0.676)	(35.861)	(0.088)
R^2	0.59	0.95	1.00	0.93
N	24,901	25,052	25,052	25,052
N-counties	232	232	232	232
Mean	9.21	3305.18	497.12	7.85
%Change	-5.78	0.03	-10.89	-1.38

▸ figure

Figure: **Effects of ECA on Infant Health**

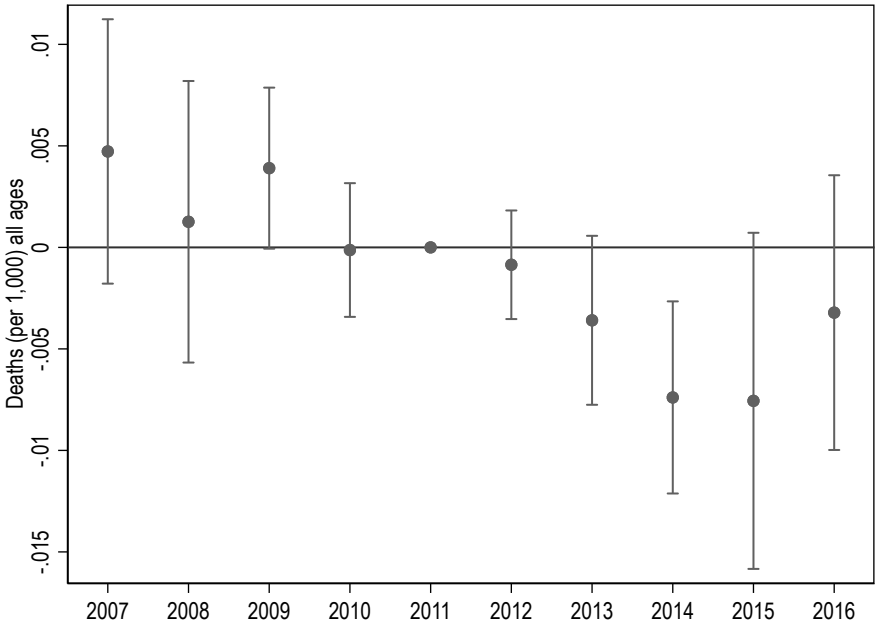


(a) Low Birth Weight

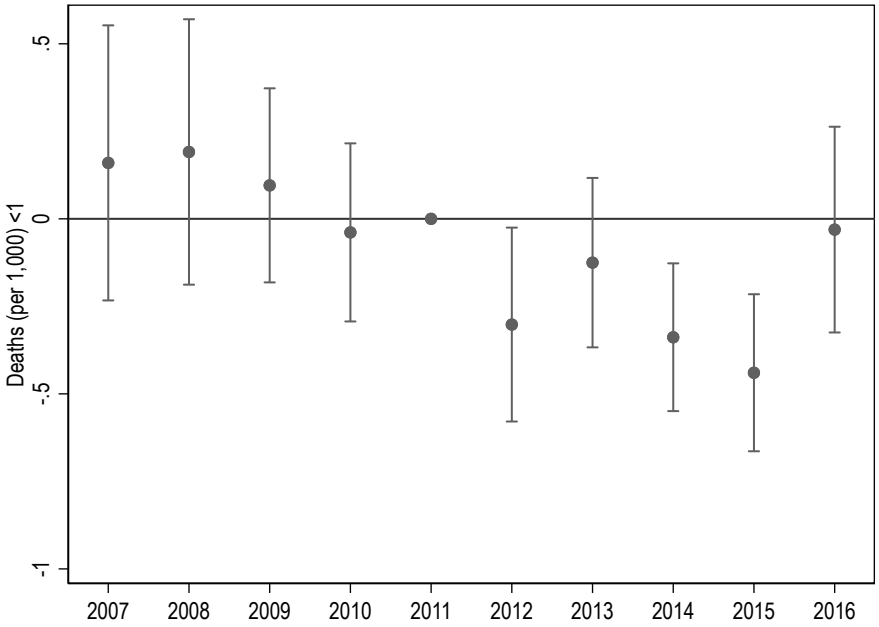


(b) Preterm Birth

Figure: **Effects of ECA on Mortality All Ages**



(a) All



(b) Under Age 1

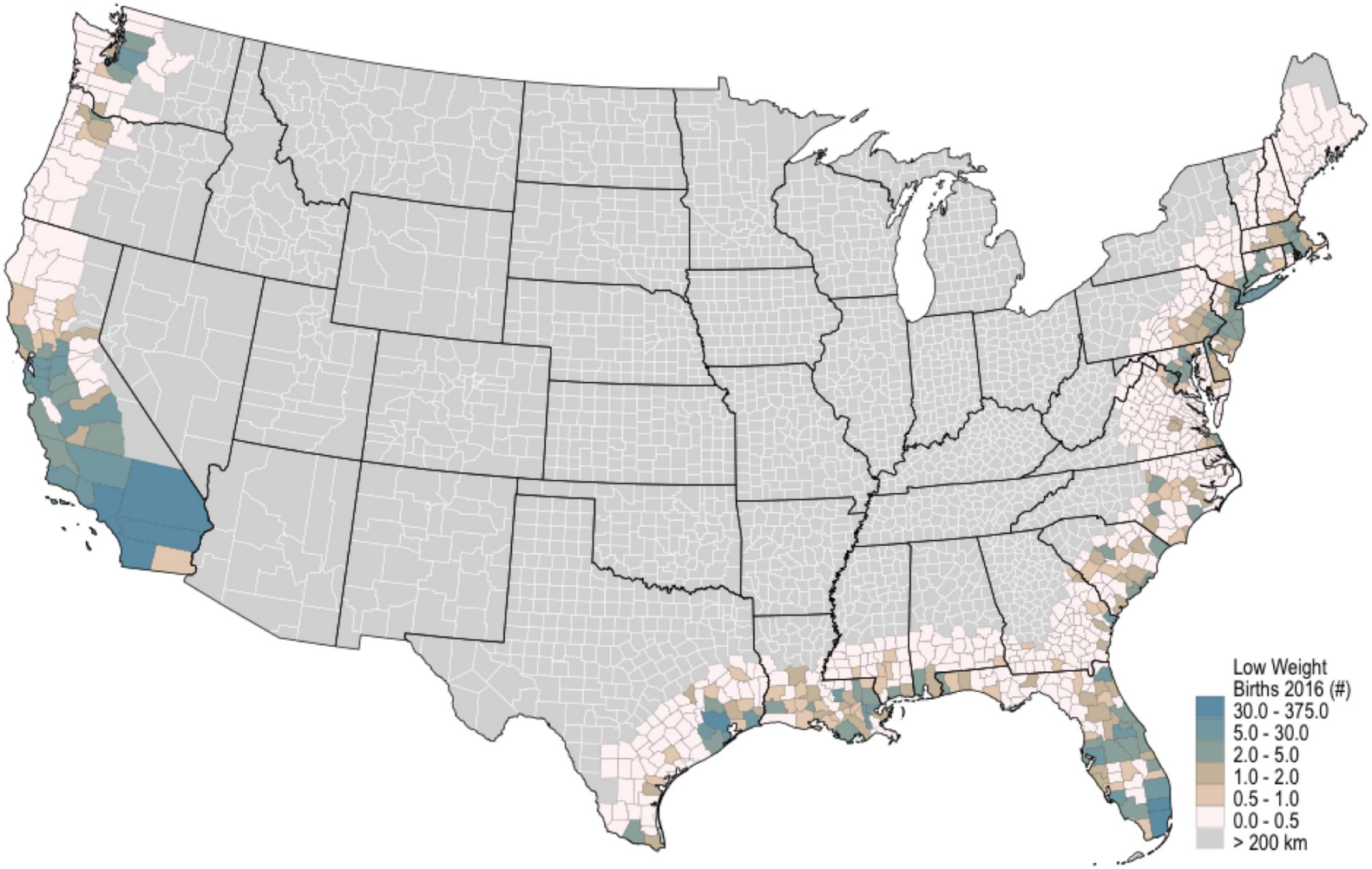
Table: **Effects of ECA on Air Pollution and Health at Birth**

	(1) Low birth weight	(2) Preterm	(3) All Deaths	(4) <1 Deaths
Post-ECA*CMAQ	-1.326	-2.082	-0.006	-0.242
	(0.348)***	(0.782)***	(0.003)**	(0.089)***
R^2	0.57	0.63	0.92	0.63
N	25,052	25,052	25,056	25,052
N-counties	232	232	232	232
Mean	60.53	93.82	0.64	6.59
%Change	-2.19	-2.22	-0.92	-3.67

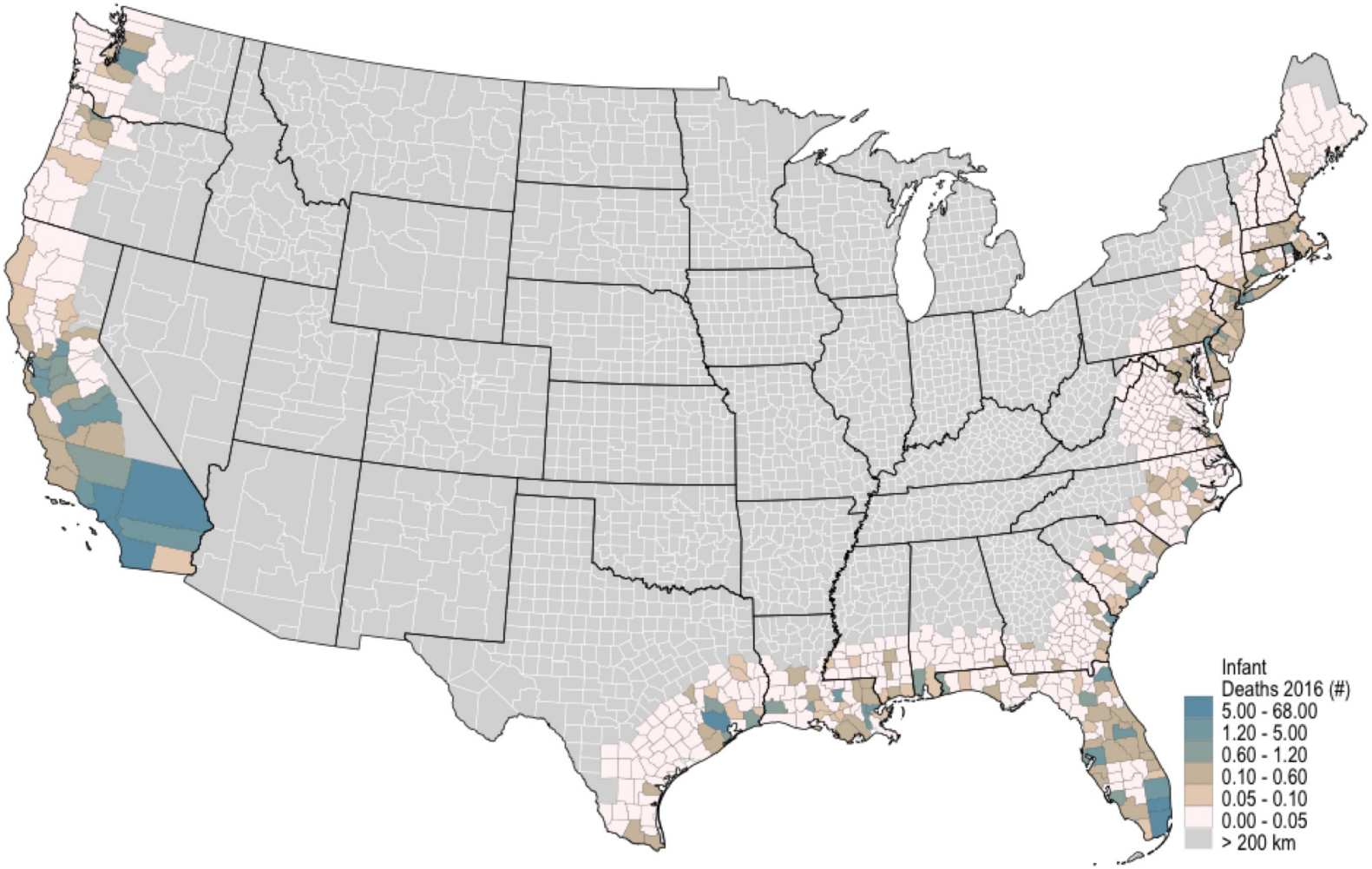
Additional Results

- Improvements for other outcomes:
  - Very low birth weight ▸ BW bins
  - Birth weight, gestation ▸ other outcomes
  - Elderly mortality ▸ elderly
- Results robust to: ▸ table
  - Cluster SE by state
  - Sample inclusion criteria
  - State-year FE
  - Flexible weather bins
  - Unbalanced panel of monitors
  - Alternate measures of CMAQ
  - Excluding port counties
  - CAA controls
- CMAQ provides increased precision relative to distance ▸ compare

1,536 (1.7%) fewer low weight births per year



228 (2.8%) fewer infant deaths per year



Outline

Behavioral Responses

Behaviors that altered the realized reduction in:

1. Air pollution:
   - Ship relocation ▸ results
   - On-land emission "rebound" ▸ results
2. Health:
   - Time spent outdoors ▸ results

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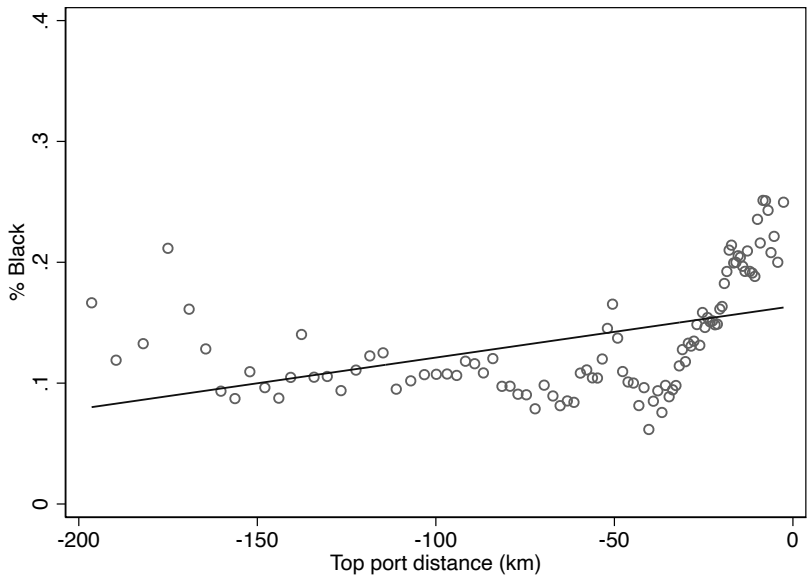
Why health effects could differ for ship emissions

- Pollution mixture: large sulfur reduction.
- Cumulative effects: sustained reduction, rather than short-run pollution fluctuation.
- Population affected: demographic composition.



(a) Distance to Ports: Black

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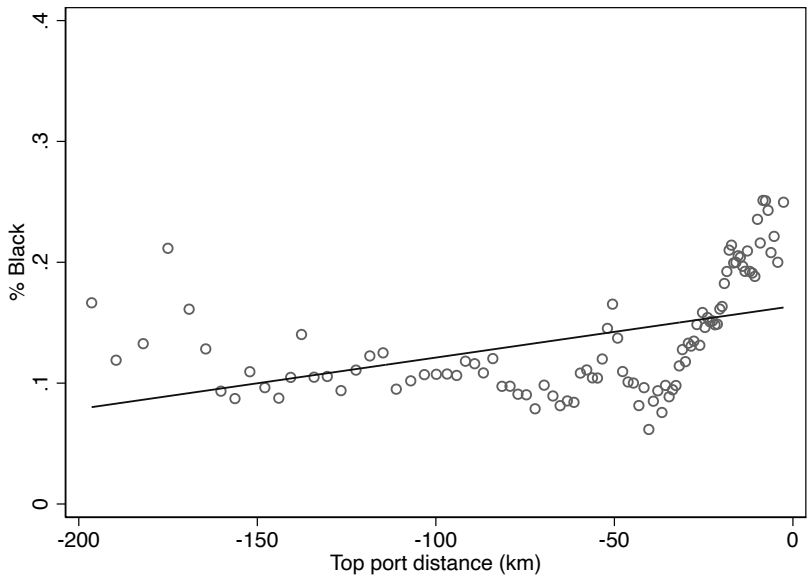
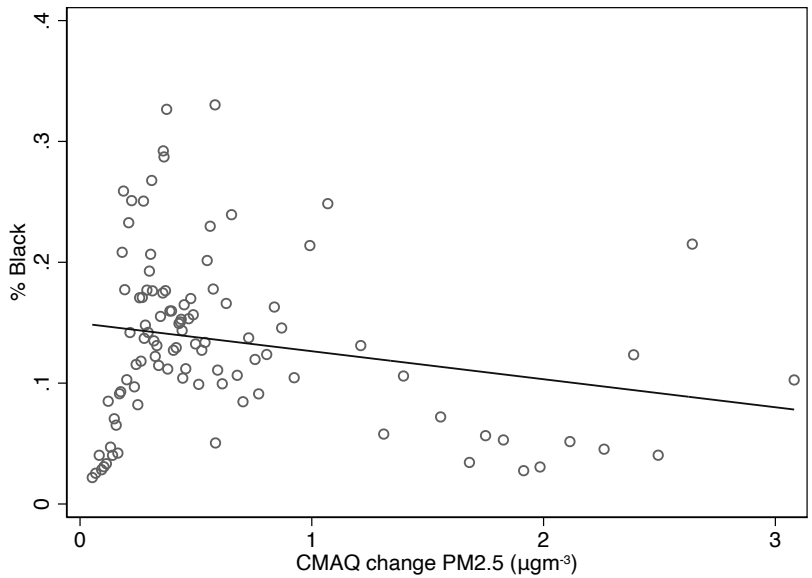


(a) Distance to Ports: Black



(b) Ship Pollution: Black

Magnitude

Table: **Comparison of Magnitude to the Literature**

Study	Outcome	Pollutant	%Δ from 10% pollutant increase
Currie and Walker 2011	Low birth weight	NO2, SO2	17.65
Alexander and Schwandt 2020	Low birth weight	PM2.5, PM10, O3	10.3
H-L and Marcus	Low birth weight	PM2.5	4.2
Chay and Greenstone 2003 A	Infant mortality	TSP	5
Chay and Greenstone 2003 B	Infant mortality	TSP	3.5
Currie and Neidell 2005	Infant mortality	CO	1.01
Luechinger 2014	Infant mortality	SO2	0.89
Gutierrez 2015	Infant mortality	PM2.5, PM10	7.1
Knittel, Miller, Sanders 2016	Infant mortality	PM10	10.3
Alexander and Schwandt 2020	Infant mortality	PM2.5, PM10, O3	9.5
H-L and Marcus	Infant mortality	PM2.5	6.2

Note: Source of calculations from Alexander and Schwandt (2021).

▸ 2sls ▸ 2sls het ▸ cdf

Outline

Discussion & Conclusion

- The US Emission Control Area:
  - reduced PM2.5 by 4% on average
  - improved health of coastal population:
    - 1,536 fewer low birth weight infants per year
    - 228 fewer deaths under age 1 per year
- Lives saved from US ECA was...
  - 1/6 of the initial 1970 CAA NAAQS (Chay and Greenstone, 2003)
  - 6x the effect of cheating diesel emissions (Alexander and Schwandt, 2021)
- 53% of forecasted pollution abatement was realized
  - evidence suggesting behavioral response by ships, other industry, and individuals not captured by ex-ante models
- 2020 IMO Global standard reduced sulfur content from 3.5% to 0.5%:
  - ≈\$10-\$60 billion per year cost to shipping industry (Corbett et al., 2016)
  - health benefits in areas without ECA

Comments/Questions:

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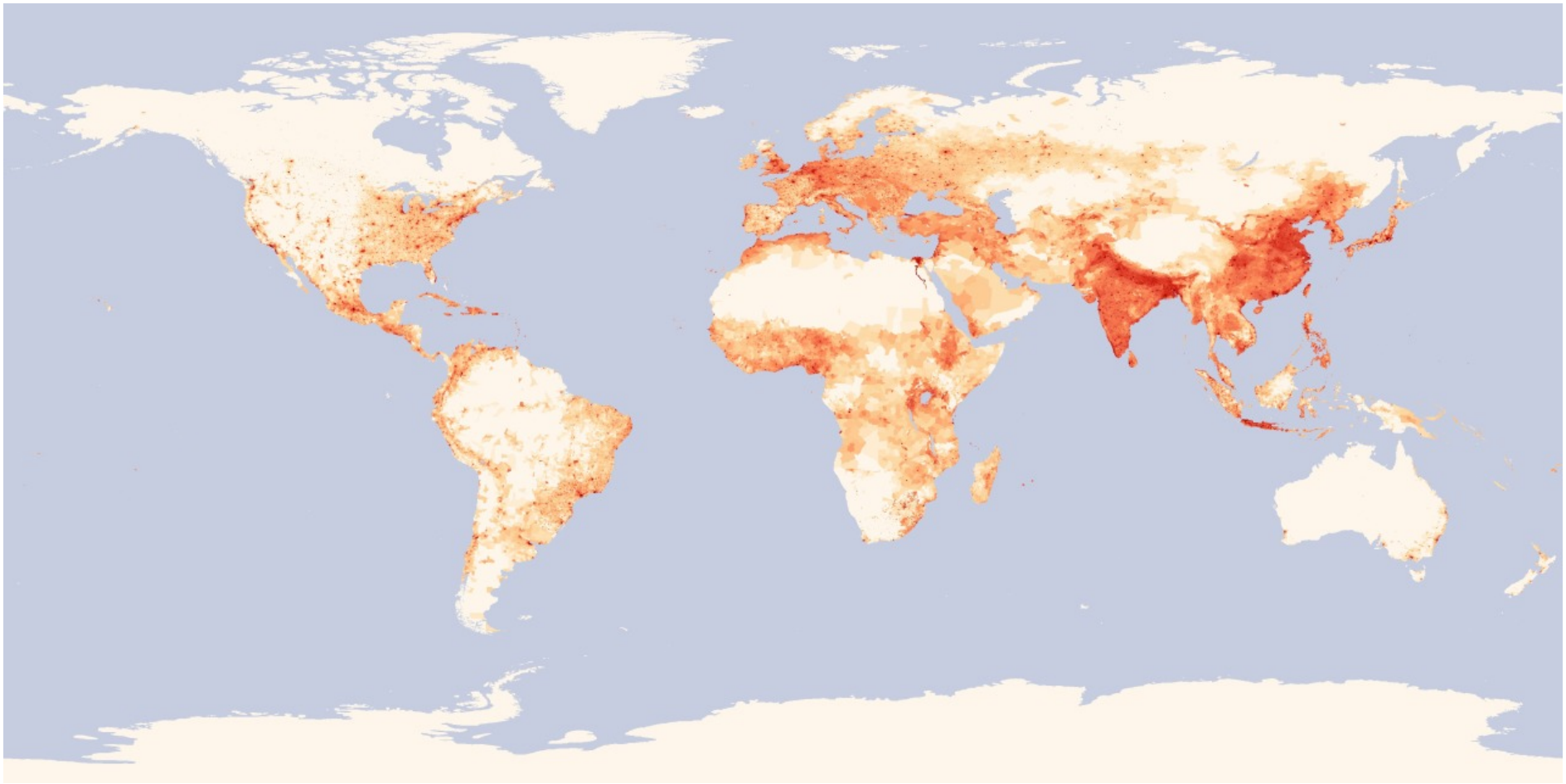
Other ECAs & 2020 IMO Global Standard

Population Distribution & 2020 IMO Global Standard



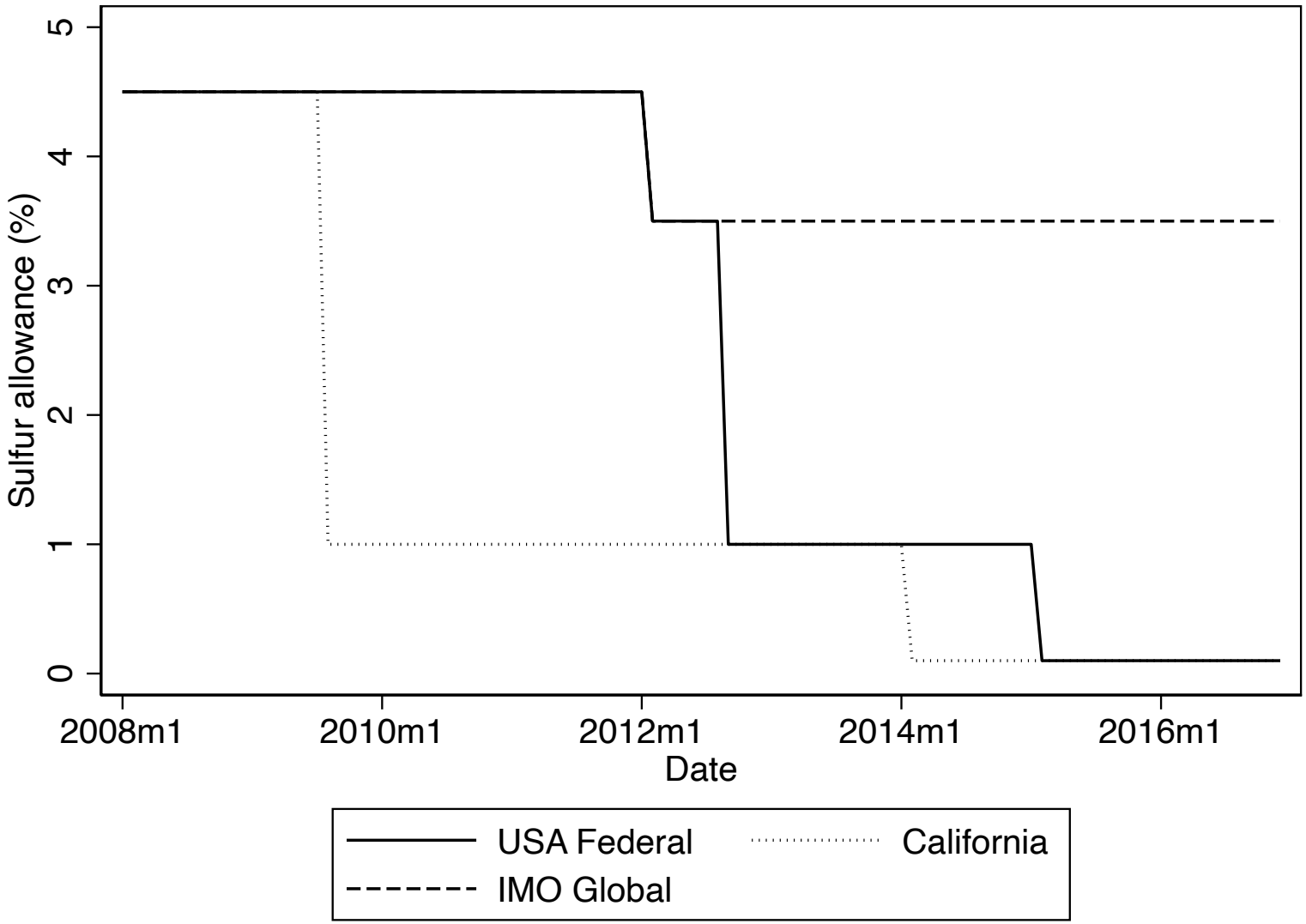
Alexander, Diane and Hannes Schwandt, "The impact of car pollution on infant and child health: Evidence from emissions cheating," *Review of Economic Studies (forthcoming)*, 2021.

Chay, Kenneth and Michael Greenstone, "Air Quality, Infant Mortality, and the Clean Air Act of 1970," *NBER Working Paper*, 2003, (w10053).

Corbett, James J, James J Winebrake, Edward W Carr, Jukka-Pekka Jalkanen, Lasse Johansson, Marje Prank, Mikhail Sofiev, SG Winebrake, and A Karppinen, "Health Impacts Associated with Delay of MARPOL Global Sulphur Standards," *IMO MEPC 70/INF*, 2016, *34*.

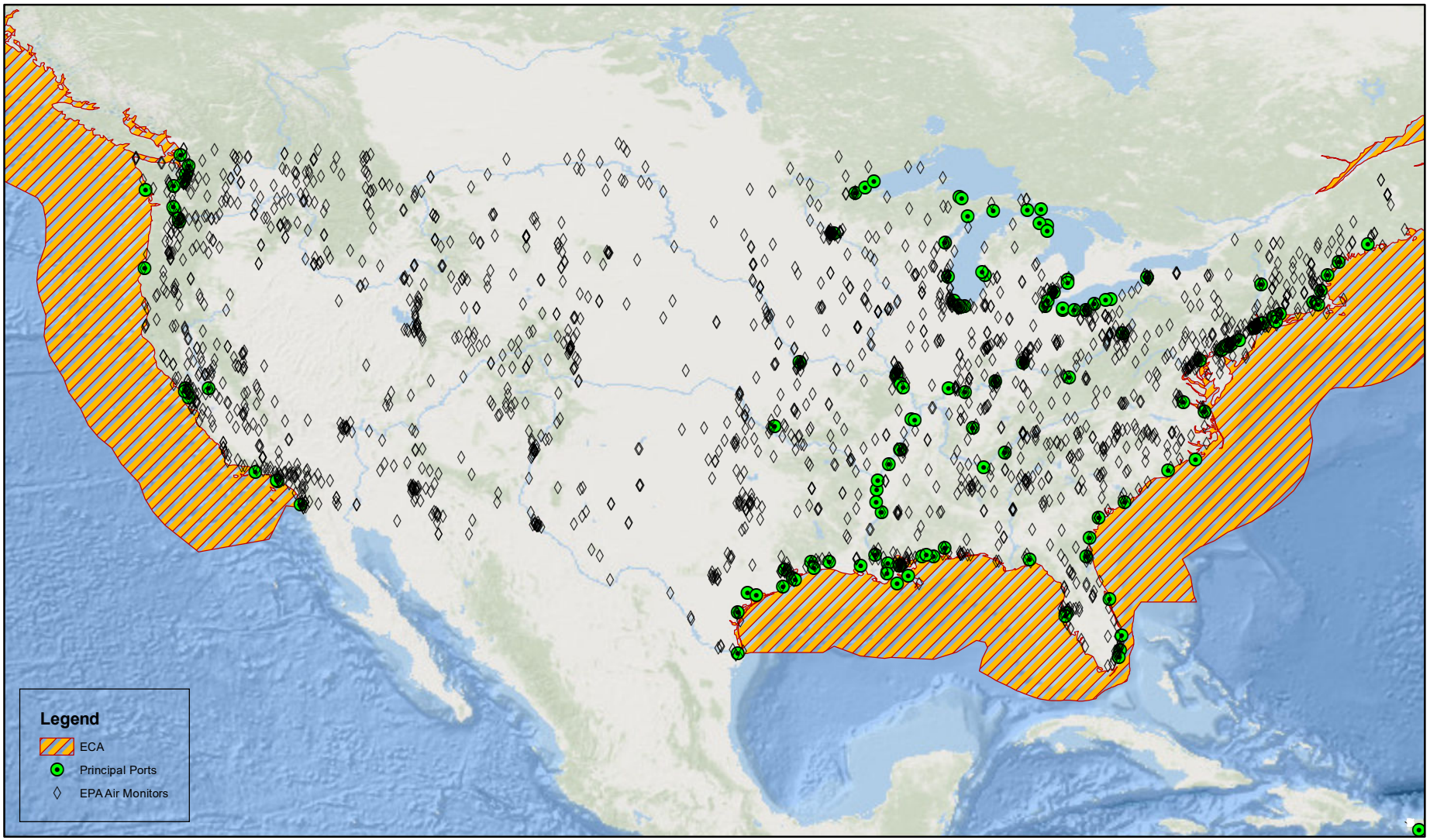
Moore, Thomas J, Jessica V Redfern, Michael Carver, Sean Hastings, Jeffrey D Adams, and Gregory K Silber, "Exploring ship traffic variability off California," *Ocean & Coastal Management*, 2018, *163*, 515–527.

Timeline of policy implementation



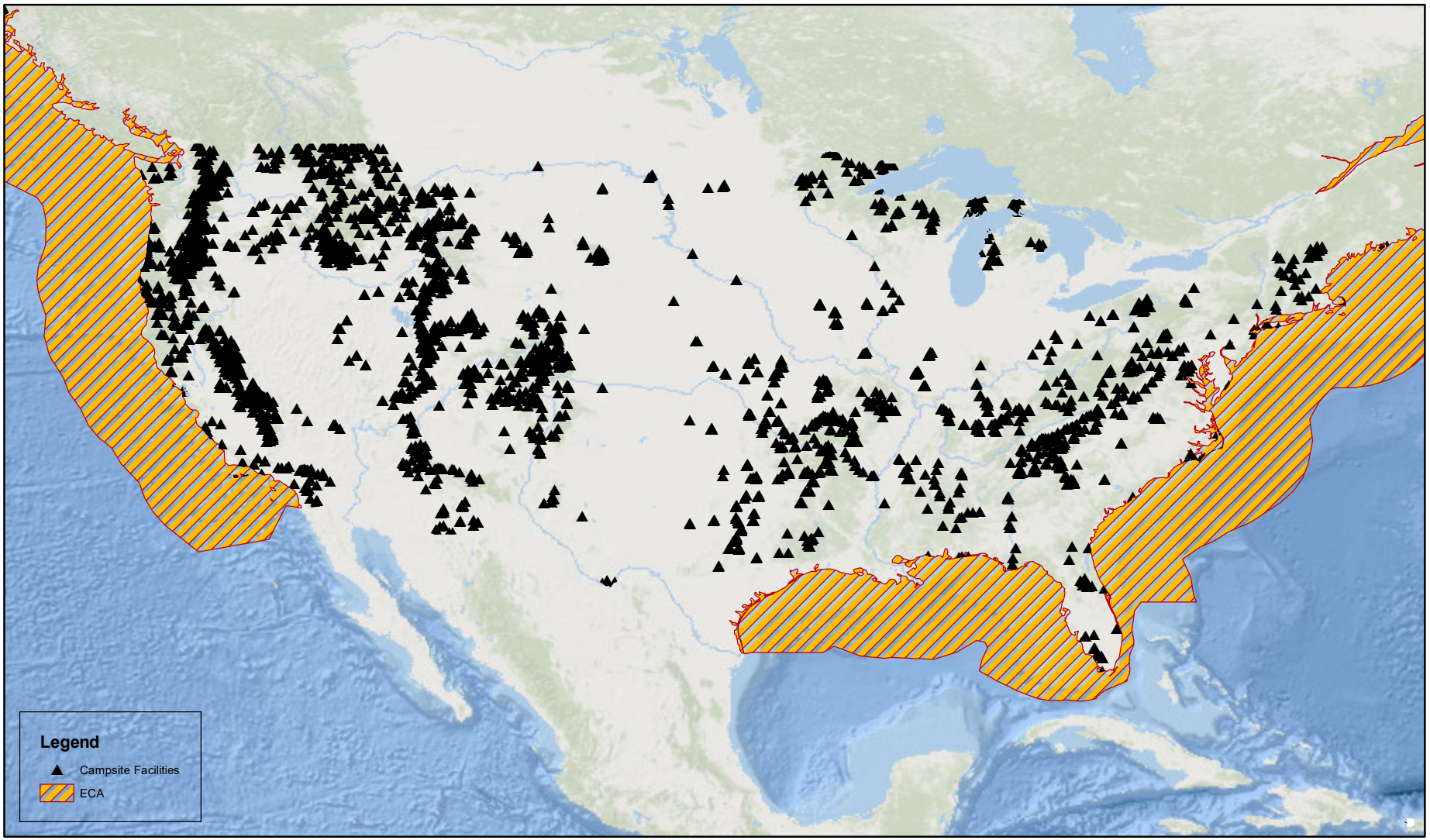
back

Figure: **Air Quality Monitors and Principal Ports**



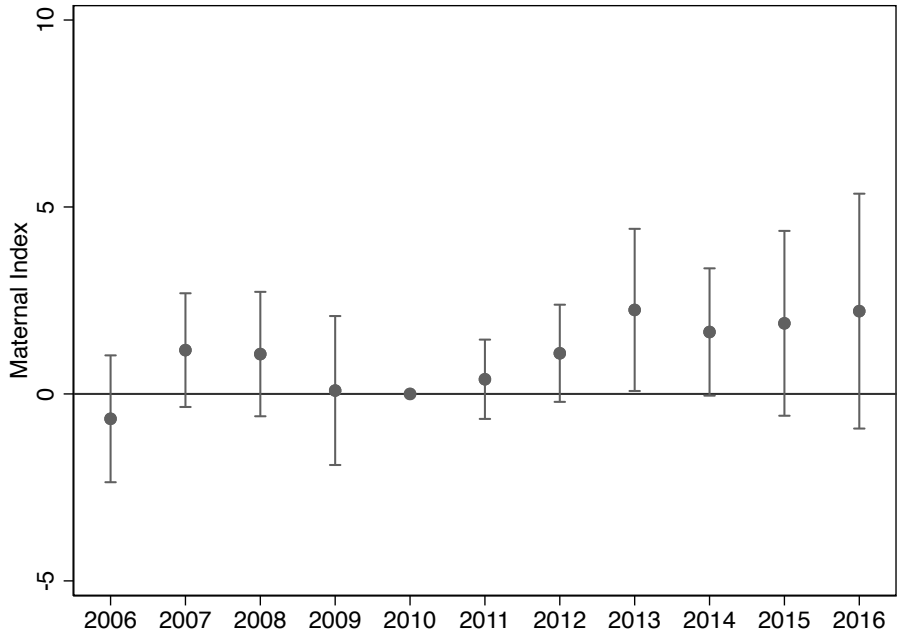
back

Figure: **Campsite Reservation Locations**



back

Figure: **Maternal Demographics and CMAQ Exposure**



back

Table: **Effects of ECA on Additional Health Outcomes**

	(1) Birth weight	(2) Gestation	(3) Deaths: 75-84	(4) Deaths: >85
Panel A. Reduced Form				
Post-ECA*CMAQ	1.622	0.012	-0.031	-0.151
	(0.874)*	(0.006)**	(0.010)***	(0.043)***
R^2	0.82	0.71	0.77	0.65
N	25,052	25,052	25,056	25,056
N-counties	232	232	232	232
Mean	3305.18	38.78	3.72	10.90
%Change	0.05	0.03	-0.83	-1.38
Panel B. 2SLS				
PM2.5	-3.445	-0.025	0.058	0.288
	(1.887)*	(0.011)**	(0.020)***	(0.081)***
R^2	0.80	0.66	0.76	0.60
N	24,901	24,901	24,905	24,905
F	19.91	19.91	30.52	29.56
N-counties	232	232	232	232
Mean	3305.10	38.78	3.72	10.90
%Change	-0.10	-0.06	1.56	2.64
Panel C. OLS				
PM2.5	0.088	-0.000	0.009	0.034
	(0.080)	(0.000)	(0.002)***	(0.004)***
R^2	0.82	0.71	0.77	0.65
N	24,901	24,901	24,905	24,905
N-counties	232	232	232	232
Mean	3305.10	38.78	3.72	10.90
%Change Post-ECA	0.00	-0.00	0.25	0.31

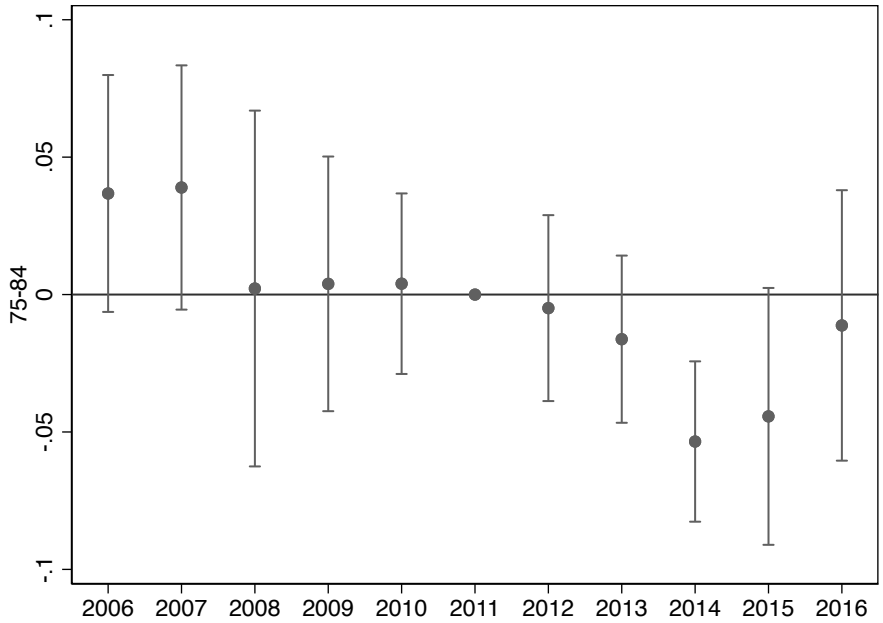
back

Table: **Effects of ECA on Distribution of Birth Weight**

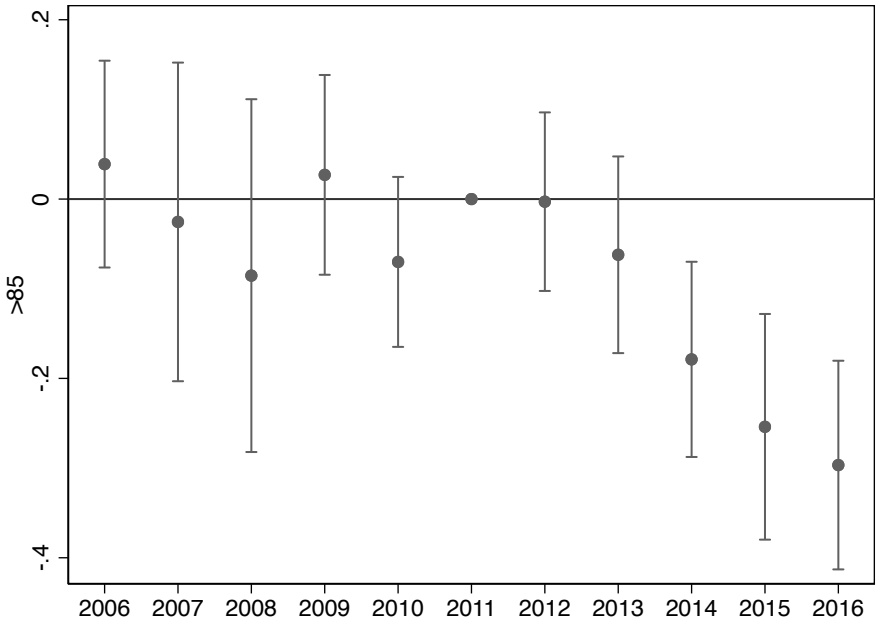
	(1) <1,000 g	(2) 1,000-1,500 g	(3) 1,500-2,000 g	(4) 2,000-2,500 g	(5) 2,500-3,000 g	(6) 3,000-3,500 g	(7) 3,500-4,000 g	(8) 4,000-4,500 g	(9) >4,500 g
Panel A. Reduced Form									
Post-ECA*CMAQ	-0.173	-0.111	-0.266	-0.777	-0.349	1.806	0.458	-0.465	-0.124
	(0.075)**	(0.073)	(0.115)**	(0.201)***	(0.593)	(0.483)***	(0.472)	(0.292)	(0.141)
R^2	0.26	0.16	0.20	0.42	0.61	0.34	0.60	0.58	0.28
N	25,052	25,052	25,052	25,052	25,052	25,052	25,052	25,052	25,052
N-counties	232	232	232	232	232	232	232	232	232
Mean	5.28	5.29	10.62	39.34	178.41	403.91	276.41	69.85	10.89
%Change	-3.27	-2.09	-2.50	-1.97	-0.20	0.45	0.17	-0.67	-1.14
Panel B. 2SLS									
PM2.5	0.364	0.233	0.555	1.629	0.780	-3.790	-0.972	0.943	0.258
	(0.171)**	(0.174)	(0.274)**	(0.624)***	(1.165)	(1.231)***	(0.997)	(0.656)	(0.314)
R^2	0.22	0.14	0.15	0.33	0.61	0.26	0.60	0.57	0.27
N	24,901	24,901	24,901	24,901	24,901	24,901	24,901	24,901	24,901
F	19.91	19.91	19.91	19.91	19.91	19.91	19.91	19.91	19.91
N-counties	232	232	232	232	232	232	232	232	232
Mean	5.28	5.29	10.62	39.35	178.44	403.94	276.38	69.82	10.89
%Change	6.89	4.41	5.22	4.14	0.44	-0.94	-0.35	1.35	2.37
Panel C. OLS									
PM2.5	-0.006	-0.003	-0.007	0.011	-0.029	-0.075	0.130	-0.029	0.007
	(0.010)	(0.010)	(0.015)	(0.027)	(0.057)	(0.057)	(0.059)**	(0.034)	(0.016)
R^2	0.26	0.16	0.20	0.42	0.61	0.34	0.60	0.58	0.28
N	24,901	24,901	24,901	24,901	24,901	24,901	24,901	24,901	24,901
N-counties	232	232	232	232	232	232	232	232	232
Mean	5.28	5.29	10.62	39.35	178.44	403.94	276.38	69.82	10.89
%Change Post-ECA	-0.11	-0.06	-0.06	0.03	-0.02	-0.02	0.05	-0.04	0.07

back

Figure: **Effects of ECA on Elderly Mortality**



(a) 75-84



(b) 85 and over

back

Table: **Robustness of Main Results**

	PM2.5		Low BW		Infant Deaths		
	(1) β	(2) p-value	(3) β	(4) p-value	(5) β	(6) p-value	(7) N clusters
(1) Baseline	-0.53	0.00	-1.33	0.00	-0.24	0.01	232.0
	(0.10)		(0.35)		(0.09)		
(2) State-level clustering	-0.53	0.00	-1.33	0.01	-0.24	0.00	25.0
	(0.12)		(0.43)		(0.05)		
(3) 150 km	-0.54	0.00	-1.32	0.00	-0.21	0.02	202.0
	(0.10)		(0.38)		(0.09)		
(4) 300 km	-0.54	0.00	-1.28	0.00	-0.25	0.01	280.0
	(0.09)		(0.32)		(0.09)		
(5) State-year FE	-0.43	0.00	-1.07	0.00	-0.21	0.03	232.0
	(0.12)		(0.32)		(0.10)		
(6) Bins of weather	-0.53	0.00	-1.37	0.00	-0.23	0.01	232.0
	(0.09)		(0.32)		(0.09)		
(7) 2009-2014 balance	-0.60	0.00	-1.38	0.00	-0.17	0.02	251.0
	(0.11)		(0.43)		(0.07)		
(8) Unbalanced panel	-0.49	0.00	-1.25	0.00	-0.24	0.00	286.0
	(0.10)		(0.31)		(0.08)		
(9) Ships' contribution	-0.36	0.00	-1.10	0.00	-0.20	0.00	232.0
	(0.10)		(0.28)		(0.07)		
(10) No ports	-0.62	0.00	-1.39	0.06	-0.51	0.00	192.0
	(0.18)		(0.74)		(0.17)		
(11) CAA controls	-0.41	0.00	-1.27	0.00	-0.24	0.02	232.0
	(0.11)		(0.34)		(0.10)		
(12) 2015 0.1ppm	-0.01	0.90	0.21	0.64	-0.04	0.68	232.0
	(0.10)		(0.45)		(0.10)		

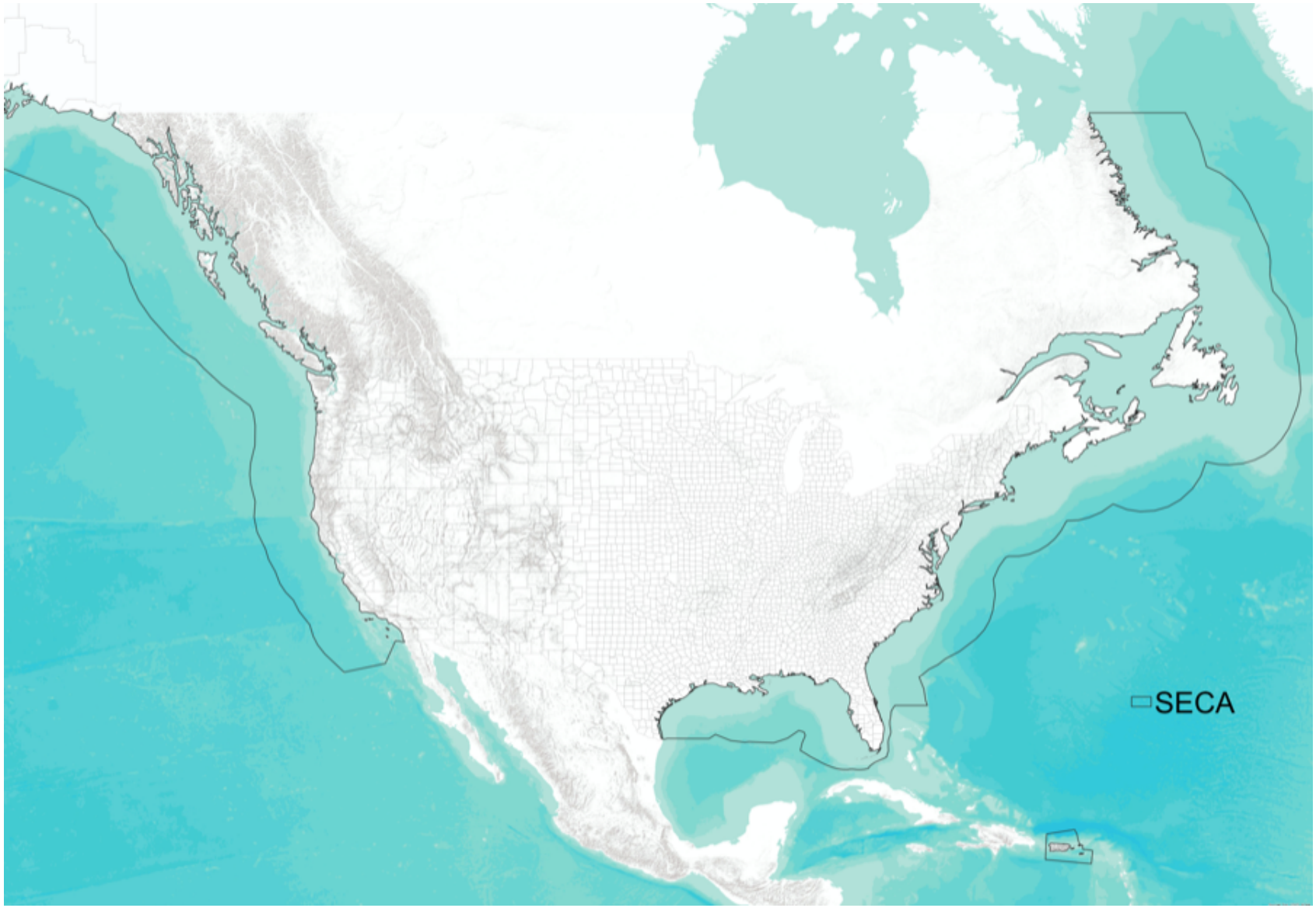
back

Table: **Comparison of Treatment Variables on Main Outcomes**

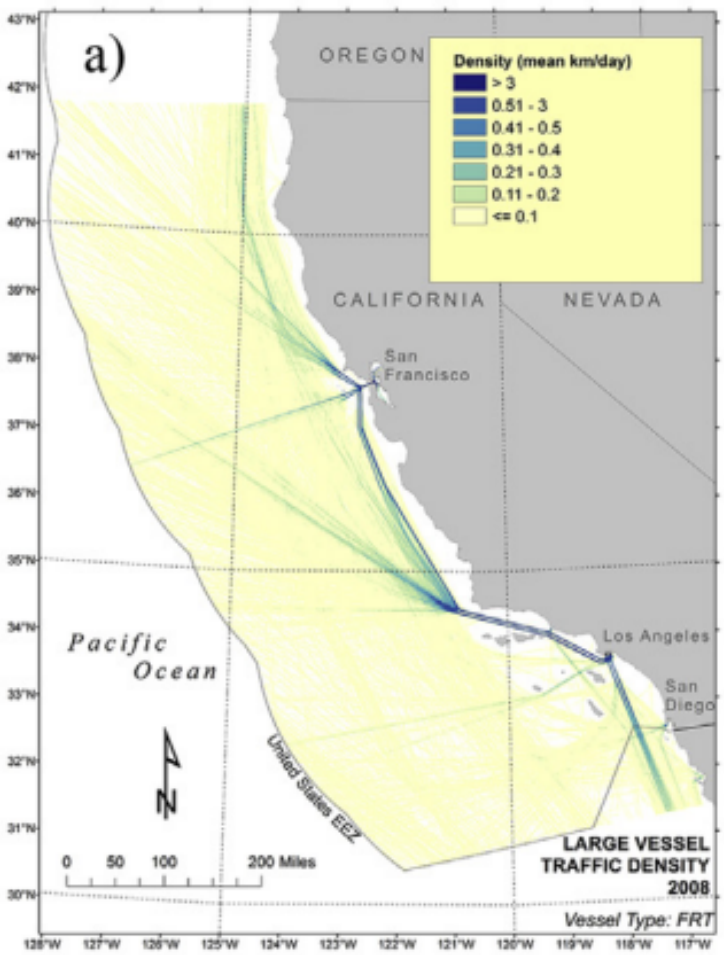
	BIC	T-stat	Coefficient	Std error
Panel A: PM2.5				
CMAQ	107,175.227	-5.575	-0.056	0.010
-Distance port	107,300.016	-1.686	-0.044	0.026
Panel B: Low birth weight				
CMAQ	190,136.703	-3.806	-0.015	0.004
-Distance port	190,155.156	-2.177	-0.019	0.009
Panel C: Infant Deaths				
CMAQ	136,256.172	-2.723	-0.010	0.004
-Distance port	136,259.469	-1.706	-0.017	0.010

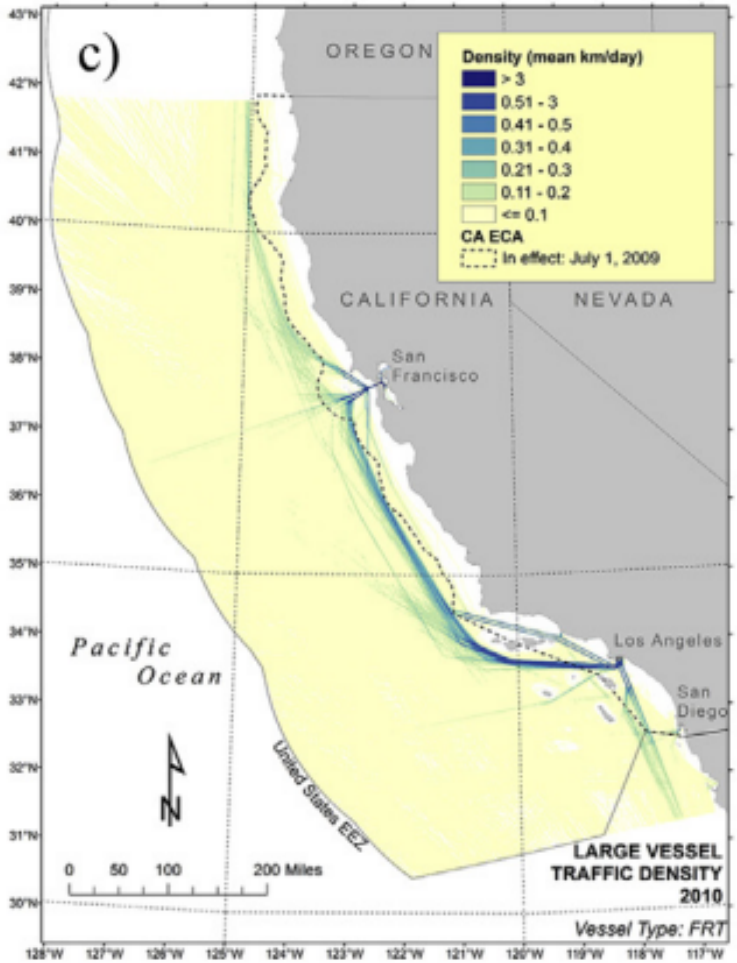
back

Emissions Control Area (ECA)



Example of avoidance of CA Policy

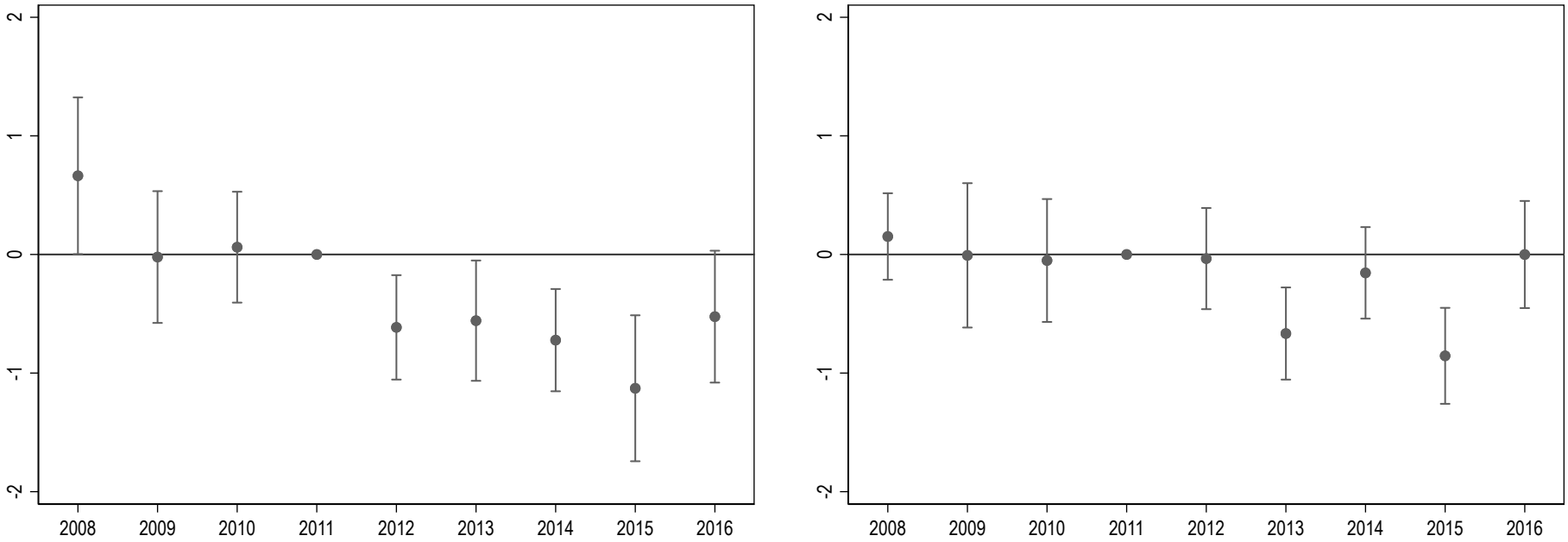




back-eca Moore et al. (2018)

Ship Behavioral Response

Figure: **Ship Behavioral Response: Full vs. Partial ECA**



(a) Full ECA

(b) Partial ECA

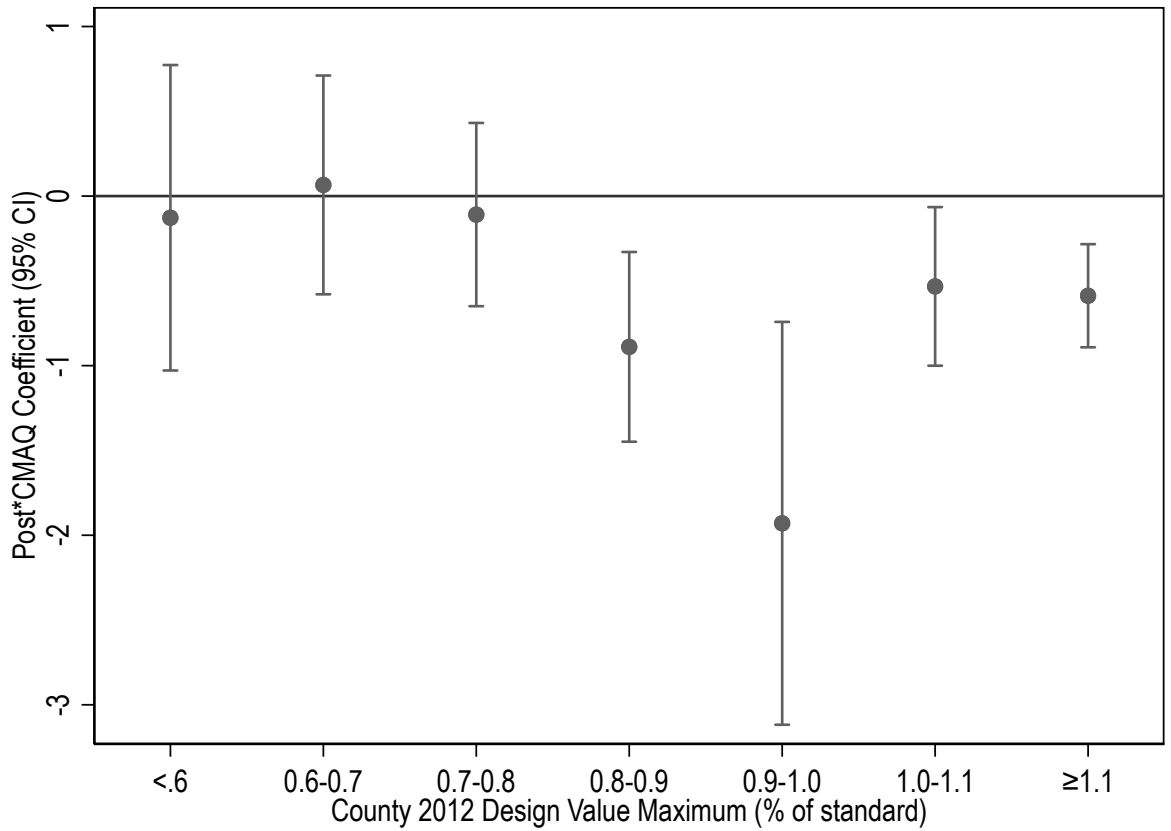
table back

Other Industry Response: "Rebound"

- Increasing emissions from other industry may offset the decline in pollution from the ECA $\rightarrow$ "regulatory rebound"
- Counties in "non-attainment" of NAAQS face costly regulation
- Counties close to the threshold of entering non-attainment are less likely offset declines from ECA by increasing emissions

Other Industry Response: "Rebound"

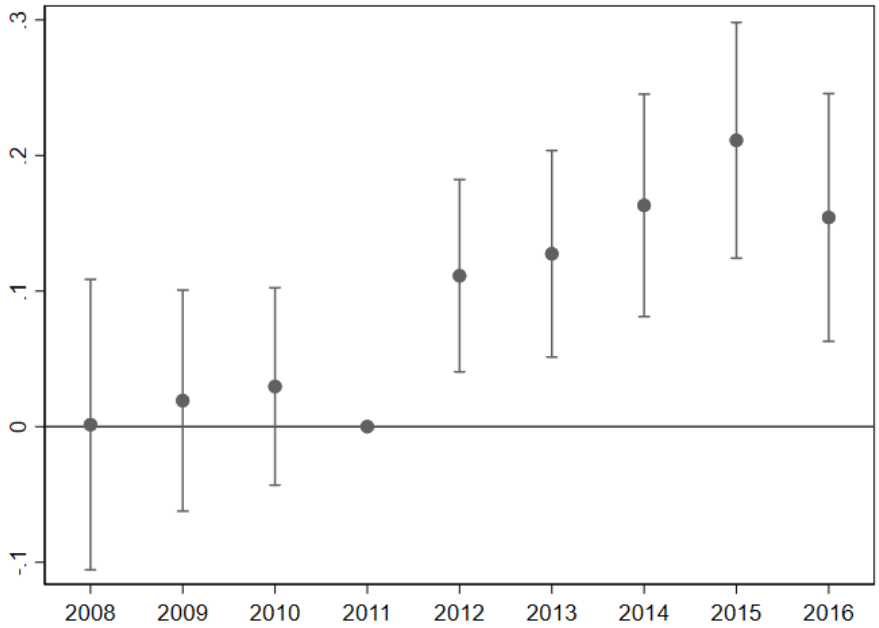
Figure: **Emissions Behavioral Response: Clean Air Act Regulatory Rebound**



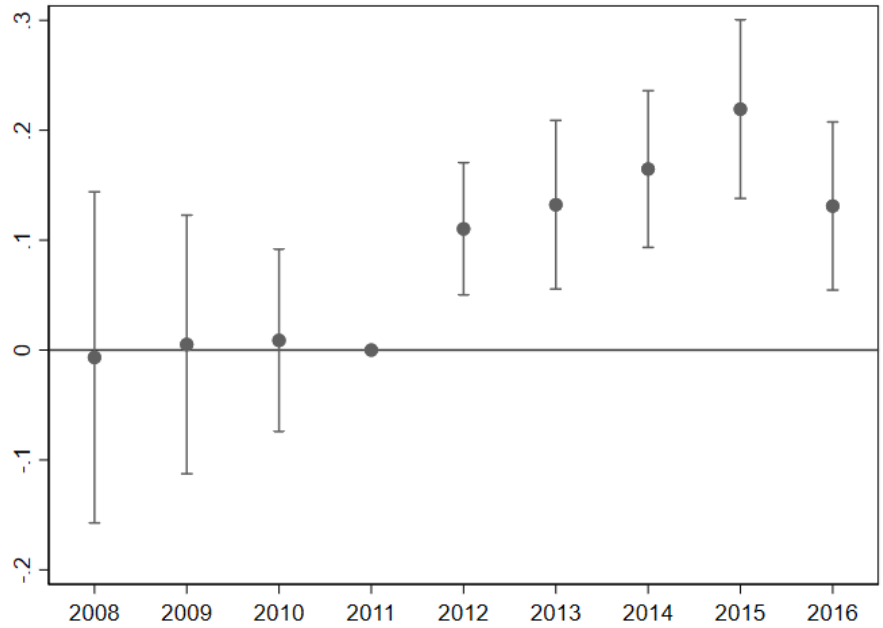
▸ table back

Individual Behavioral Response

Figure: **Individual Behavioral Response: Campsite Reservations**



(a) Log Visits



(b) Log Days

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Table: **2SLS Effects PM2.5 on Health**

	(1) Low birth weight	(2) Preterm	(3) All Deaths	(4) <1 Deaths
PM2.5	2.780	4.305	0.011	0.443
	(1.062)***	(2.165)**	(0.006)*	(0.201)**
R^2	0.45	0.52	0.91	0.61
N	24,901	24,901	24,905	24,901
F	19.91	19.91	33.47	30.29
N-counties	232	232	232	232
Mean	60.54	93.82	0.64	6.59
%Change	4.59	4.59	1.72	6.72

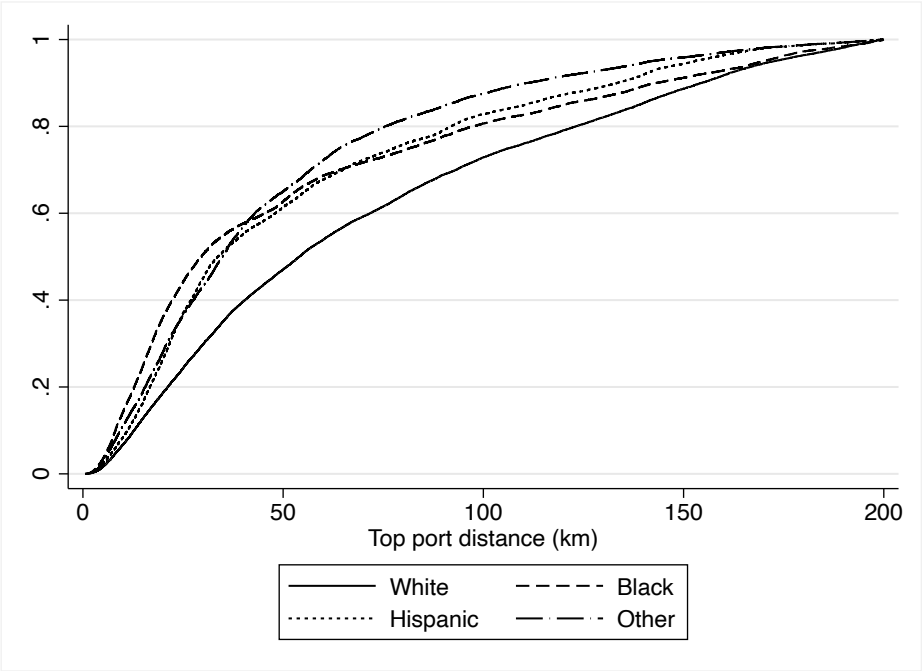
back

Table: **Heterogeneity across individuals: Low Birth Weight**

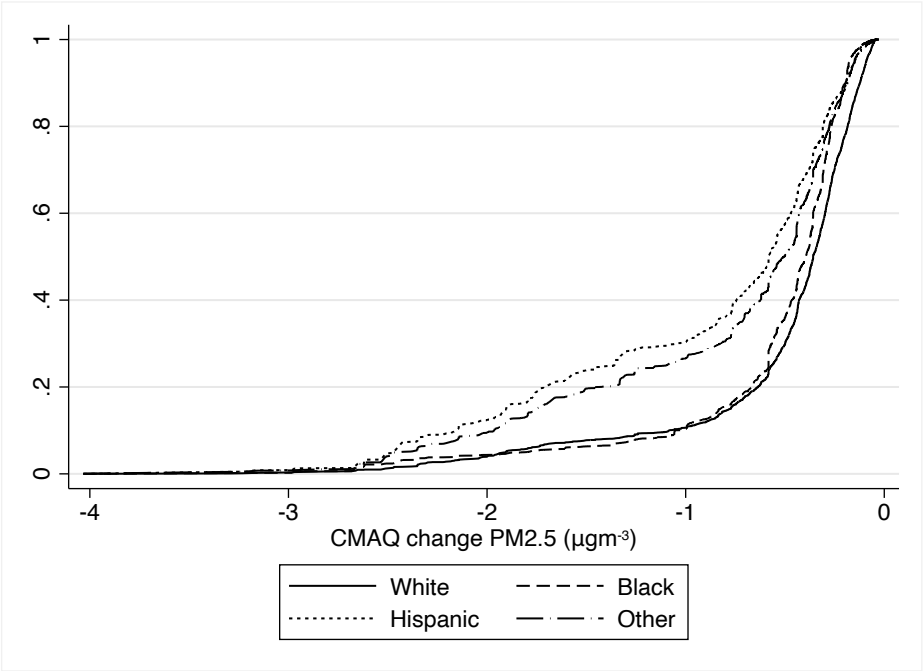
	(1) All	(2) NH White	(3) NH Black	(4) NH Other	(5) Hispanic
PM2.5	0.00277	0.00307	0.00223	0.00792	0.00113
	(0.00093)***	(0.00151)**	(0.00267)	(0.00211)***	(0.00063)*
R^2	0.01	0.01	0.01	0.00	0.00
N	12,426,807	5,062,128	1,860,002	1,337,613	4,167,051
F	23.56	12.48	11.76	28.83	26.18
N-counties	232	232	232	231	232
Mean	0.06	0.05	0.11	0.06	0.06
%Change	4.57	6.56	2.09	12.59	2.02

back

Exposure Demographics



(a) Distance to Port



(b) CMAQ Exposure

back

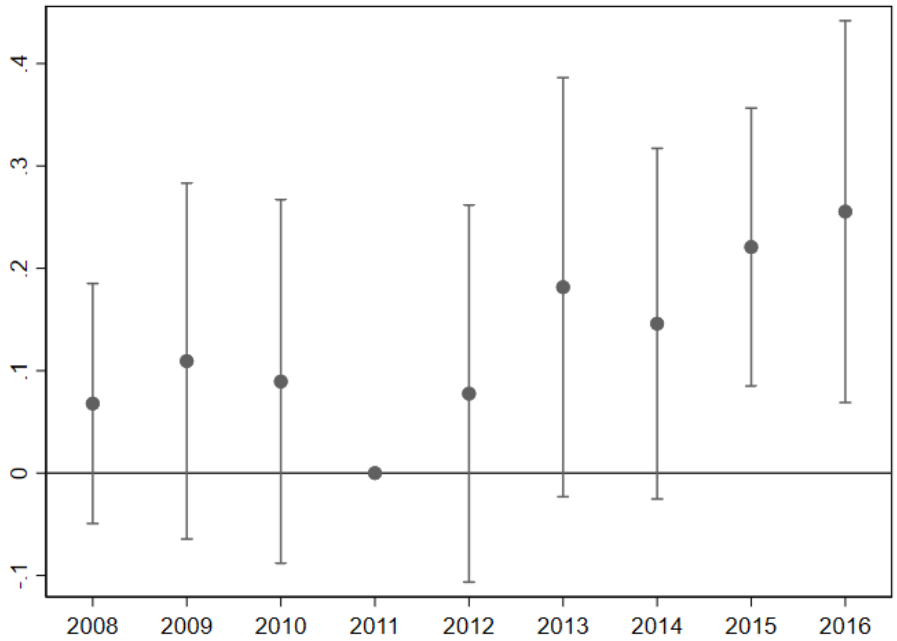
Table: **Effect of ECA on Ship and Other Emissions Behavior**

	(1) PM2.5	(2) PM2.5	(3) PM2.5
Post*CMAQ	-0.577	-0.865	-1.935
	(0.125)***	(0.186)***	(0.599)***
Post*CMAQ*𝟙(ECA<200nm)		0.426	
		(0.172)**	
Post*CMAQ*𝟙(0.8<DV)			1.895
			(0.555)***
Post*CMAQ*𝟙(0.8 $\leq$ DV $<$ 0.9)			1.043
			(0.588)*
Post*CMAQ*𝟙(DV $\geq$ 1.0)			1.361
			(0.575)**
R^2	0.59	0.59	0.55
N	24,905	24,905	19,992
N-counties	232	232	186
Mean	8.30	8.30	8.72
% Change:			
All	-6.96		
ECA=200nm		-10.47	
ECA<200nm		-5.14	
DV $<$ 0.8			-0.53
0.8 $\leq$ DV $<$ 0.9			-10.62
0.9 $\leq$ DV $<$ 1.0			-19.20
DV $\geq$ 1.0			-6.04

size caa

Individual Behavioral Response

Figure: **Individual Behavioral Response: Time Spent Outdoors**



back

Table: **Effect of ECA on Individual Behavior**

	Campsite Reservations (Log)						Time Outdoors
	Visits	Visits	People	People	Days	Days	(IHS)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
post-ECA × CMAQ	0.114***	0.146***	0.104**	0.144***	0.111**	0.150***	0.0797*
	(0.0429)	(0.0335)	(0.0456)	(0.0362)	(0.0471)	(0.0310)	(0.0473)
Region-year FE	X	X	X	X	X	X	X
County-season FE	X		X		X		X
Facility-month FE		X		X		X	
Year-month FE		X		X		X	X
R-squared	0.357	0.934	0.420	0.899	0.399	0.933	0.064
Observations	37,765	37,374	37,764	37,373	36,212	35,811	29,516
N-counties	149	143	149	143	141	135	183

back

Table: **Time Outdoors: Placebo Tests**

	(1) Sleep	(2) Housework	(3) Groceries
post-ECA × CMAQ	0.00112	0.0486	-0.0235
	(0.00669)	(0.0691)	(0.0301)
Region-year FE	X	X	X
County-season FE	X	X	X
Year-month FE	X	X	X
R-squared	0.083	0.153	0.063
Observations	29,516	29,516	29,516
N-counties	183	183	183

back