Supporting Information

Quantifying the Effects of Energy Infrastructure on Bird Populations and Biodiversity

Erik Katovich

Institute of Economics and Econometrics, University of Geneva

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Summary: Number of pages is 21; number of figures is 18; number of tables is 6.

A Supplementary Figures

A.1 Explanation of Christmas Bird Count Circles

Figure A1: Schematic of CBC Circle, Buffer Zone, and Turbine/Well Treatment Definitions

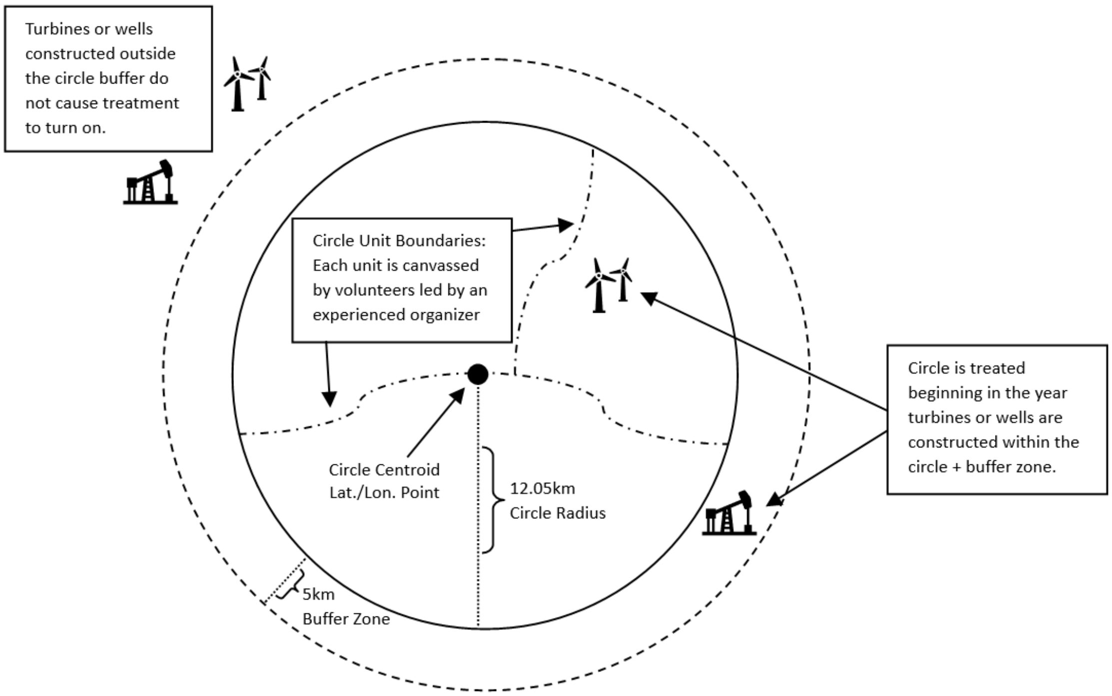
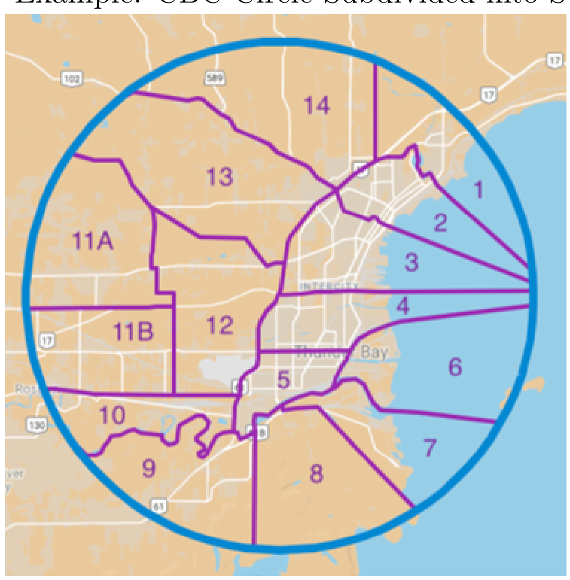


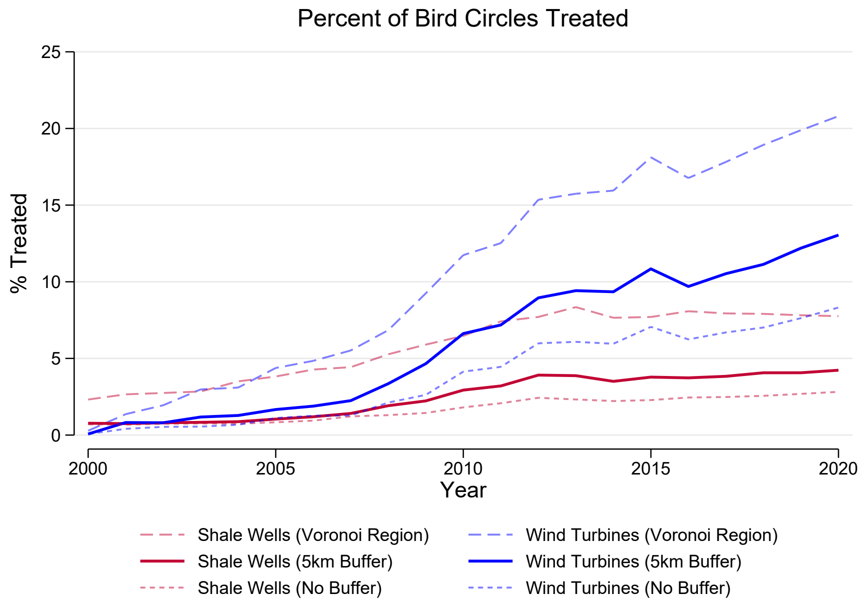
Figure A2: Example: CBC Circle Subdivided into Survey Units



Source: Thunder Bay Field Naturalists (2021)

A.2 Percentage of Circles Treated Over Time

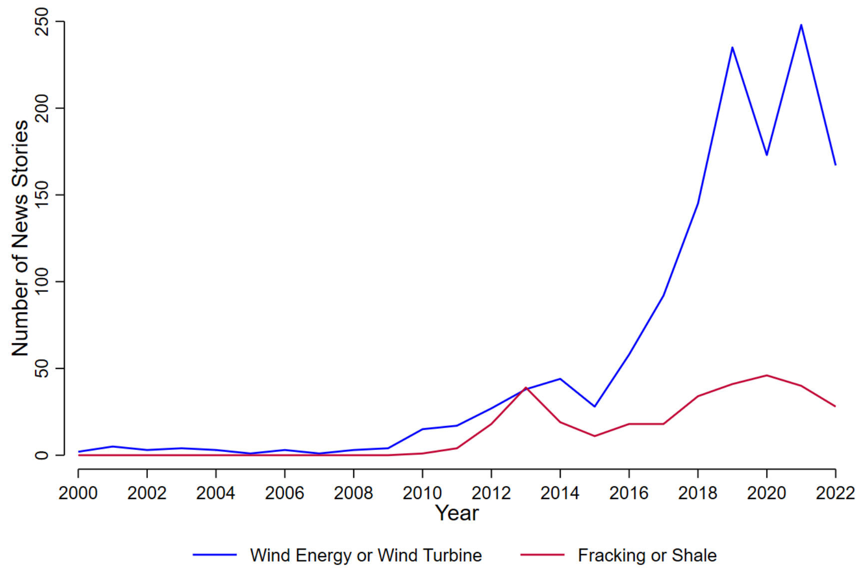
Figure A3: Percentage of Circles Treated (2000-2020)



Note: Percentage of CBC Circles with shale well or wind turbine presence (2000-2020), under alternative treatment definitions.

A.3 News Coverage of Energy Infrastructure Impacts on Birds

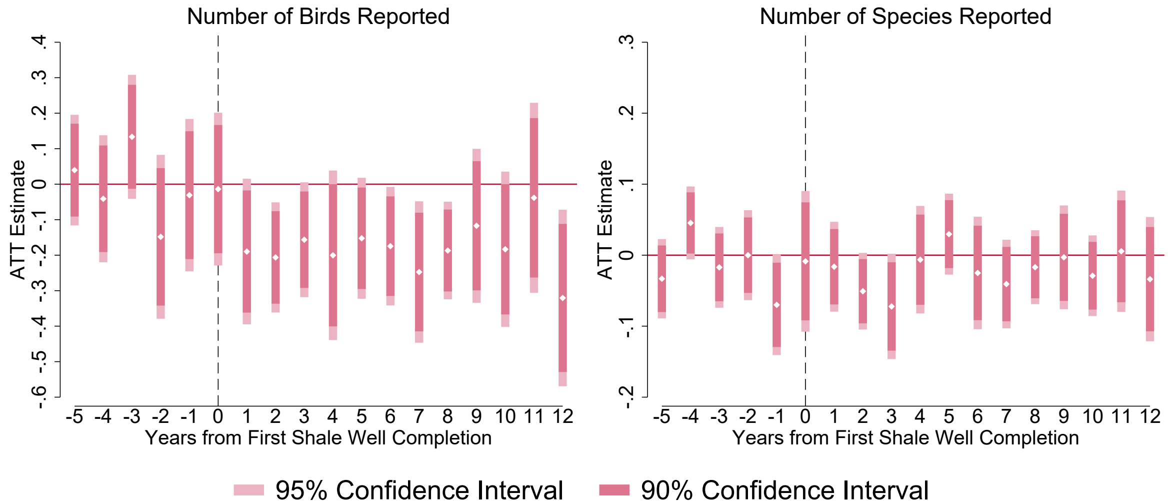
Figure A4: US News Coverage of Wind and Shale Effects on Birds



Note: Number of US news stories covering effects of wind or shale on birds, from the International Newsstream Database. Keyword searches were conducted for (i) "Birds" AND ("Fracking" OR "Shale") and (ii) "Birds" AND ("Wind Energy" OR "Turbines"). News stories were restricted to the United States between Jan. 1st 2000 and Dec. 31st 2022.

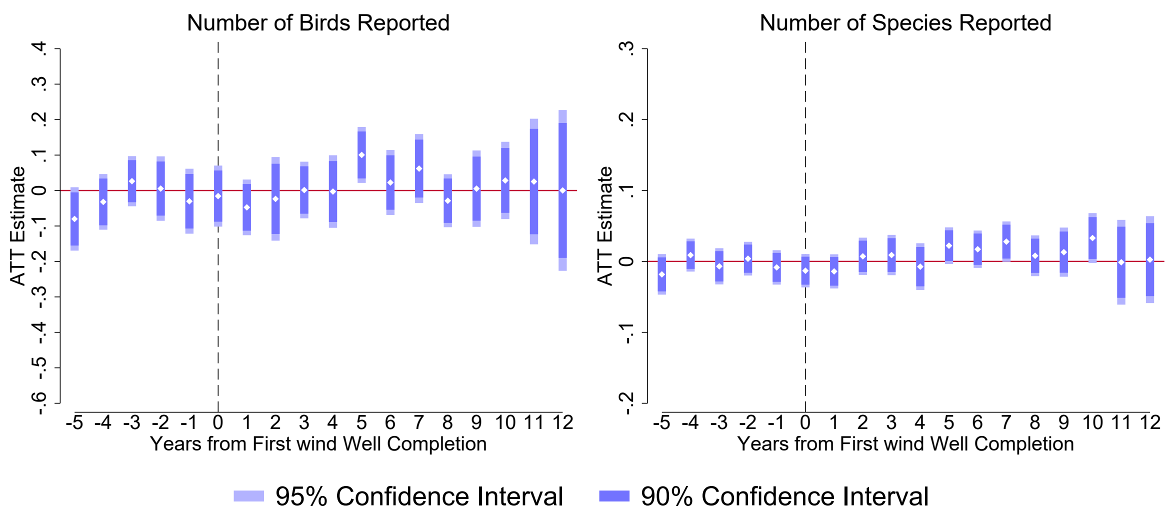
A.4 Event Studies: Number of Birds Counted

Figure A5: Effects of Shale Wells on Bird and Species Counts (Dynamic)



Note: Figure reports coefficient estimates with 90% and 95% confidence intervals from event studies that regress number of birds or species counted on relative time indicators around the year of arrival of shale wells within 5km of a CBC circle. Specifications include year and circle fixed effects and a vector of covariates including (i) number of counters and (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count. Standard errors are clustered at the circle level and the model is estimated using CALLAWAY2021200's *csdid* estimator. Continuous outcomes are transformed using the inverse hyperbolic sine function. Statistically insignificant effect estimates prior to arrival of shale wells support the identifying parallel pre-trends assumption, i.e, prior to well arrival, circles with wells were evolving on a similar trajectory to places without wells.

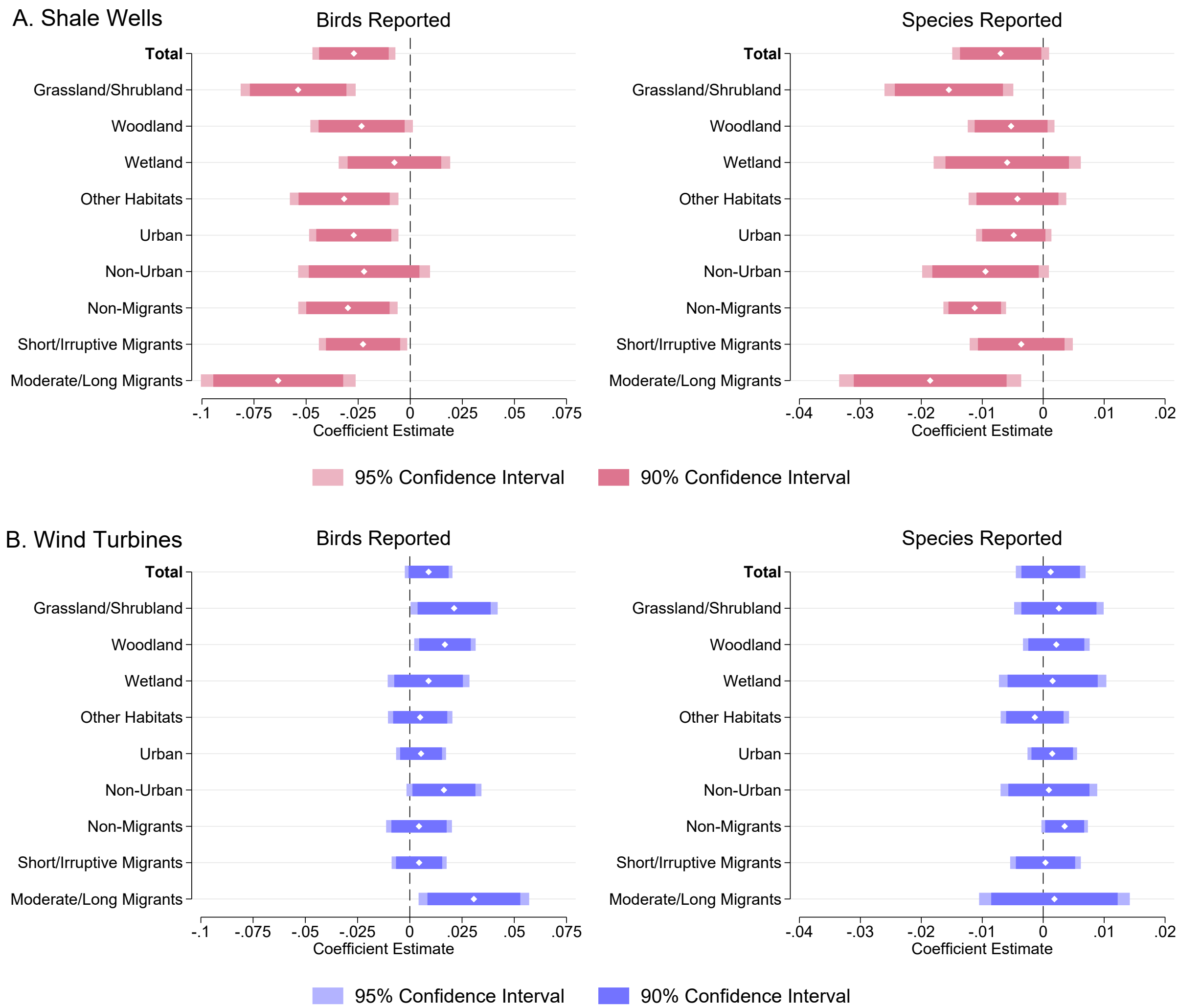
Figure A6: Effects of Wind Turbines on Bird and Species Counts (Dynamic)



Note: Figure reports coefficient estimates with 90% and 95% confidence intervals from event studies that regress number of birds or species counted on relative time indicators around the year of arrival of wind turbines within 5km of a CBC circle. Specifications include year and circle fixed effects and a vector of covariates including (i) number of counters and (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count. Standard errors are clustered at the circle level and the model is estimated using CALLAWAY2021200's *csdid* estimator. Continuous outcomes are transformed using the inverse hyperbolic sine function. Statistically insignificant effect estimates prior to arrival of wind turbines support the identifying parallel pre-trends assumption, i.e, prior to turbine arrival, circles with turbines were evolving on a similar trajectory to places without turbines.

A.5 Results with Continuous Treatment

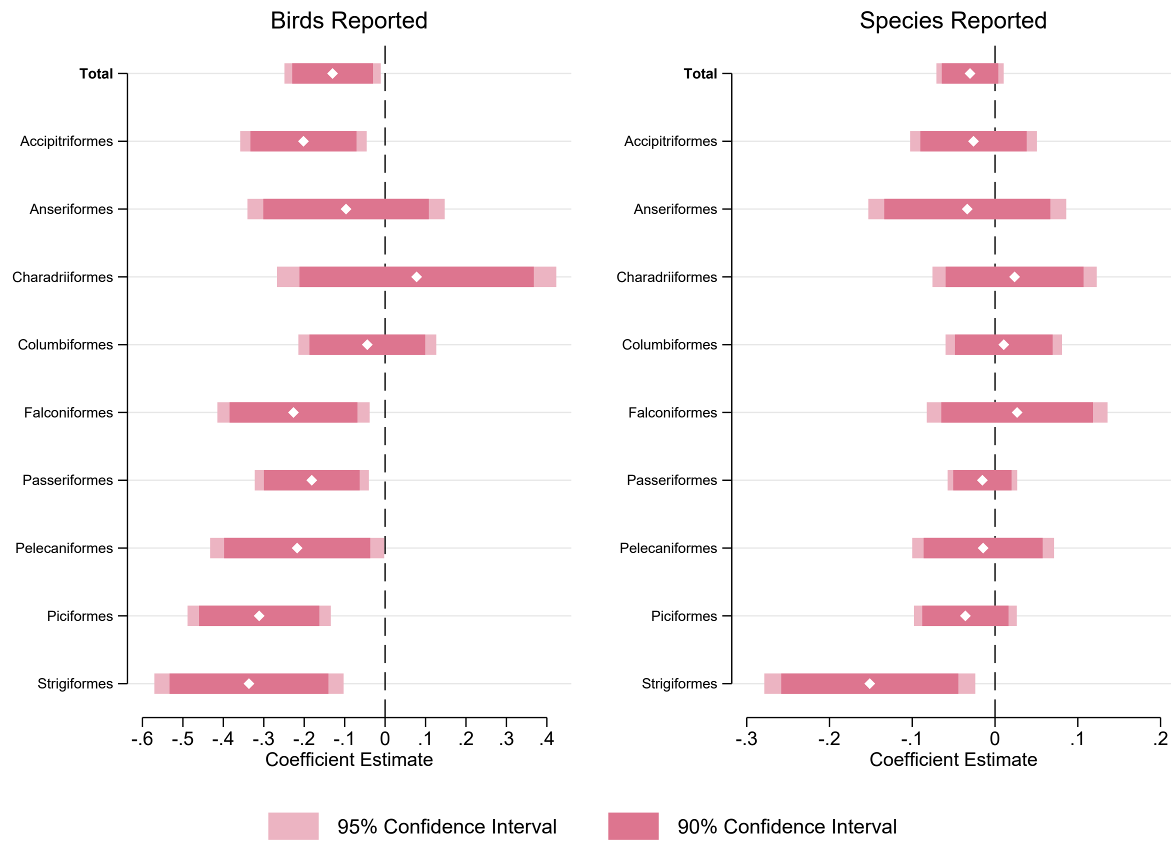
Figure A7: Poisson Model with Untransformed Counts



Figures report coefficient estimates with 90% and 95% confidence intervals from estimation of a Poisson model of birds or species counted (total and disaggregated by bird characteristic), using a continuous treatment definition (i.e., the inverse hyperbolic sine of the cumulative number of shale wells or wind turbines operating within 5km of a CBC circle). Specifications include year and circle fixed effects and a vector of covariates including (i) number of counters, (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count, and (iii) proportions of the CBC circle occupied by agriculture, pasture, and developed land-uses. Robust standard errors are reported.

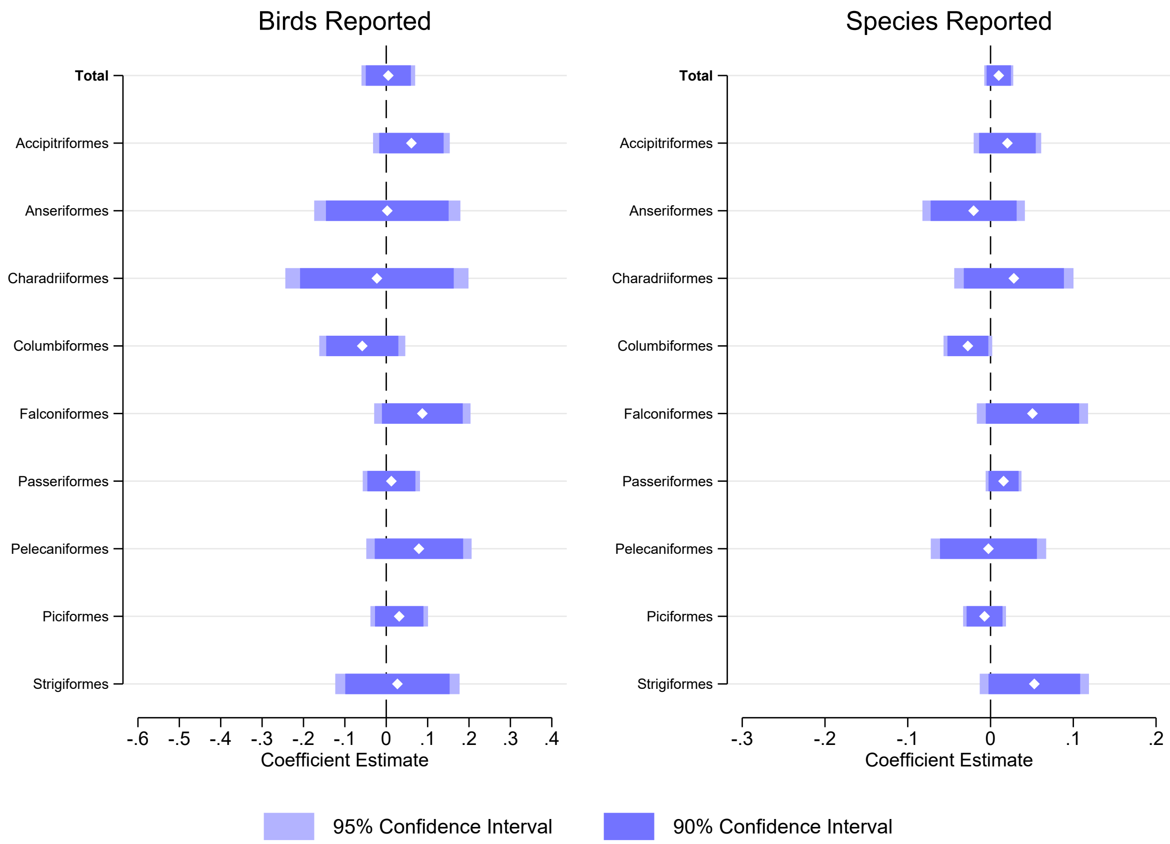
A.6 Results Disaggregated by Taxonomic Order

Figure A8: Effects of Shale Well Arrival on Bird and Species Counts
(Disaggregated by Order)



Notes: Figure reports coefficient estimates with 90% and 95% confidence intervals from difference-in-differences specifications that regress number of birds or species counted (total and disaggregated by bird order) on relative time indicators around the year shale wells were first drilled within 5km of the border of a CBC circle (control group = never-treated circles). Specifications include year and circle fixed effects and a vector of covariates including (i) number of counters and (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count. Standard errors are clustered at the circle level and the model is estimated using Callaway and Sant'Anna's *csdid* estimator to accommodate staggered treatment timing and heterogeneous treatment effects

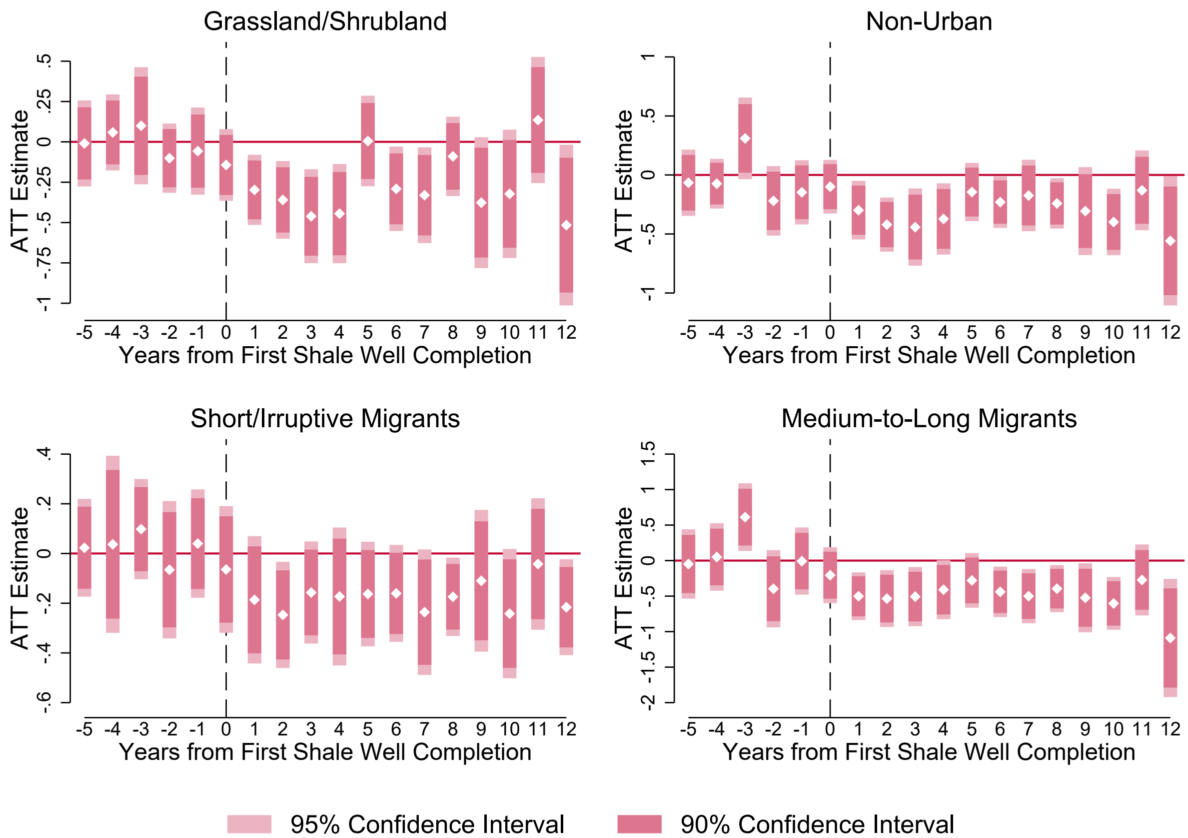
Figure A9: Effects of Wind Turbine Arrival on Bird and Species Counts (Disaggregated by Order)



Notes: Figure reports coefficient estimates with 90% and 95% confidence intervals from difference-in-differences specifications that regress number of birds or species counted (total and disaggregated by bird order) on relative time indicators around the year wind turbines were first installed within 5km of the border of a CBC circle (control group = never-treated circles). Specifications include year and circle fixed effects and a vector of covariates including (i) number of counters and (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count. Standard errors are clustered at the circle level and the model is estimated using Callaway and Sant'Anna's *csdid* estimator to accommodate staggered treatment timing and heterogeneous treatment effects

A.7 Additional Event Studies for Shale Well Impacts

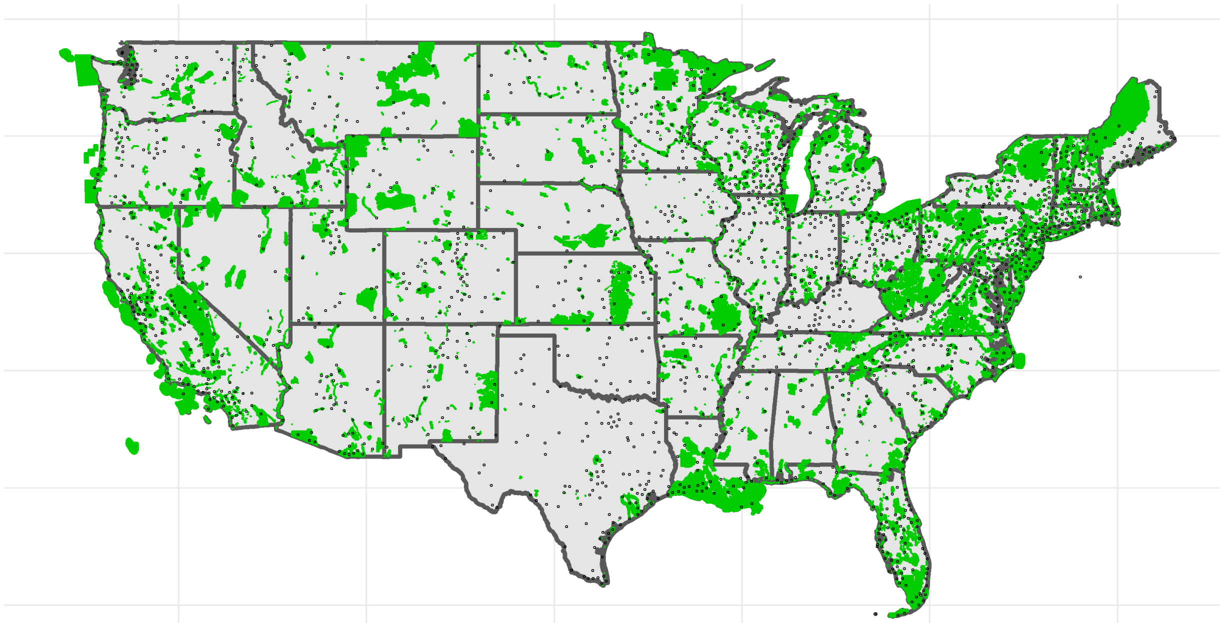
Figure A10: Shale Well Arrival: Event Studies for Selected Characteristics



Note: Figures are constructed as described in Appendix Figure A5.

A.8 Map of Important Bird Areas

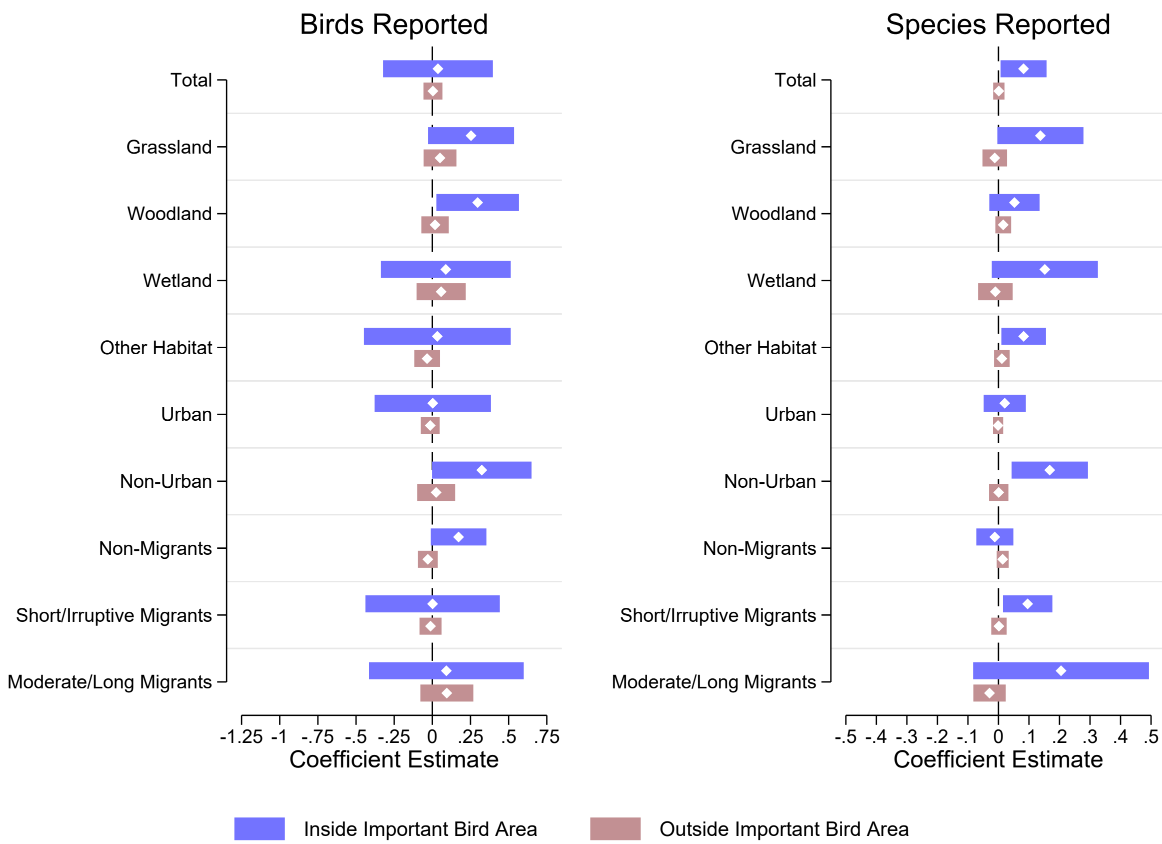
Figure A11: CBC Circle Locations Relative to Important Bird Areas (in Green)



Source: Audobon2023a.

A.9 Results Heterogeneity: Inside/Outside Important Bird Areas

Figure A12: Effects of Wind Turbine Arrival Inside/Outside Important Bird Areas (Disaggregated by Characteristic)



Notes: Figure reports coefficient estimates with 90% and 95% confidence intervals from difference-in-differences specifications that regress number of birds or species counted (total and disaggregated by bird characteristic) on relative period indicators before and after the year wind turbines were first constructed within 5km of a CBC circle (control group = never-treated circles). Specifications are estimated separately for CBC circles inside and outside important bird areas. Specifications include year and circle fixed effects and a vector of covariates including (i) number of counters, (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count, and (iii) proportions of the CBC circle occupied by agriculture, pasture, and developed land-uses. Standard errors are clustered at the circle level and the model is estimated using Callaway and Sant'Anna's *csdid* estimator. Continuous outcomes are transformed using the inverse hyperbolic since function.

B Supplementary Tables

B.1 Results: Shale Wells

Table B1: Results: Effects of Shale Wells on Bird Population Count (Disaggregated by Characteristic)

	Total	*Grassland*	*Woodland*	*Wetland*	*Other Habitat*	*Urban*	*Non-Urban*	*Residents*	*Short Mig.*	*Longer Mig.*
Coef. (CS)	-0.161	-0.275	-0.171	-0.222	-0.125	-0.153	-0.264	-0.157	-0.185	-0.464
St. Error	(0.064)	(0.086)	(0.087)	(0.104)	(0.086)	(0.061)	(0.082)	(0.067)	(0.069)	(0.119)
p-val	0.012	0.001	0.049	0.033	0.144	0.012	0.001	0.020	0.008	0.000
Coef. (Poisson)	-0.027	-0.054	-0.023	-0.008	-0.032	-0.027	-0.022	-0.030	-0.023	-0.063
St. Error	(0.010)	(0.014)	(0.013)	(0.014)	(0.013)	(0.011)	(0.016)	(0.012)	(0.011)	(0.019)
p-val	0.008	0.000	0.063	0.578	0.017	0.013	0.170	0.014	0.036	0.001
n (CS)	26,462	26,357	26,442	26,195	26,461	26,461	26,462	26,443	26,462	26,000
n (Poisson)	26,805	26,704	26,785	26,539	26,804	26,804	26,805	26,786	26,805	26,328
DV Mean	8,253	822	1,148	2,428	3,539	6,057	2,196	1,097	6,326	830

Note: Upper panel of the table reports coefficient estimates, standard errors, and p-values from difference-in-differences specifications that regress number of birds counted (total and disaggregated by characteristic) on relative period indicators before and after the year shale wells were first drilled within 5km of the border of a CBC circle (control group = never-treated circles) using CALLAWAY2021200's *csdid* estimator (CS); continuous variables are transformed using the inverse hyperbolic since function. Middle panel reports analogous results estimated using Poisson and continuous treatment (number of wells), with untransformed count data. All specifications include year and circle fixed effects and a vector of covariates including (i) number of counters, (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count, and (iii) proportions of the CBC circle occupied by agriculture, pasture, and developed land-uses. Standard errors are clustered at the circle level. Bottom panel reports sample sizes and baseline dependent variable means.

Table B2: Results: Effects of Shale Wells on Bird Species Count (Disaggregated by Characteristic)

	Total	*Grassland*	*Woodland*	*Wetland*	*Other Habitat*	*Urban*	*Non-Urban*	*Residents*	*Short Mig.*	*Longer Mig.*
Coef. (CS)	-0.031	-0.061	-0.029	-0.015	-0.011	-0.023	-0.055	-0.039	-0.019	-0.029
St. Error	(0.023)	(0.030)	(0.033)	(0.058)	(0.021)	(0.020)	(0.035)	(0.023)	(0.029)	(0.052)
p-val	0.177	0.04	0.383	0.791	0.623	0.25	0.117	0.09	0.508	0.578
Coef. (Poisson)	-0.007	-0.015	-0.005	-0.006	-0.004	-0.005	-0.009	-0.011	-0.004	-0.019
St. Error	(0.004)	(0.005)	(0.004)	(0.006)	(0.004)	(0.003)	(0.005)	(0.003)	(0.004)	(0.008)
p-val	0.085	0.004	0.147	0.338	0.301	0.126	0.075	0.000	0.404	0.015
n (CS)	26,462	26,357	26,442	26,195	26,461	26,461	26,462	26,443	26,462	26,000
n (Poisson)	26,805	26,704	26,785	26,539	26,804	26,804	26,805	26,786	26,805	26,328
DV Mean	66.6	11.8	22.3	18.3	13.5	33.7	33.0	14.4	43.8	8.4

Note: Refer to note under Table B1.

B.2 Results: Wind Turbines

Table B3: Results: Effects of Wind Turbines on Bird Population Count (Disaggregated by Characteristic)

	Total	*Grassland*	*Woodland*	*Wetland*	*Other Habitat*	*Urban*	*Non-Urban*	*Residents*	*Short Mig.*	*Longer Mig.*
Coef. (CS)	0.005	0.087	0.060	0.046	-0.031	-0.016	0.061	0.012	-0.019	0.098
St. Error	(0.035)	(0.052)	(0.045)	(0.074)	(0.045)	(0.035)	(0.059)	(0.032)	(0.041)	(0.080)
p-val	0.883	0.092	0.184	0.532	0.490	0.653	0.296	0.712	0.648	0.225
Coef. (Poisson)	0.009	0.021	0.017	0.009	0.005	0.005	0.016	0.004	0.004	0.031
St. Error	(0.006)	(0.011)	(0.007)	(0.010)	(0.008)	(0.006)	(0.009)	(0.008)	(0.007)	(0.014)
p-val	0.122	0.046	0.025	0.368	0.528	0.376	0.074	0.583	0.507	0.023
n (CS)	26,570	26,468	26,550	26,309	26,569	26,569	26,570	26,551	26,570	26,096
n (Poisson)	26,805	26,704	26,785	26,539	26,804	26,804	26,805	26,786	26,805	26,328
DV Mean	10,248	912	1,356	3,512	3,919	7,397	2,851	1,420	7,551	1,276

Note: Upper panel of the table reports coefficient estimates, standard errors, and p-values from difference-in-differences specifications that regress number of birds counted (total and disaggregated by characteristic) on relative period indicators before and after the year wind turbines were first constructed within 5km of the border of a CBC circle (control group = never-treated circles) using CALLAWAY2021200's *csdid* estimator (CS); continuous variables are transformed using the inverse hyperbolic since function. Middle panel reports analogous results estimated using Poisson and continuous treatment (number of wells), with untransformed count data. All specifications include year and circle fixed effects and a vector of covariates including (i) number of counters, (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count, and (iii) proportions of the CBC circle occupied by agriculture, pasture, and developed land-uses. Standard errors are clustered at the circle level. Bottom panel reports sample sizes and baseline dependent variable means.

Table B4: Results: Effects of Wind Turbines on Bird Species Count (Disaggregated by Characteristic)

	Total	*Grassland*	*Woodland*	*Wetland*	*Other Habitat*	*Urban*	*Non-Urban*	*Residents*	*Short Mig.*	*Longer Mig.*
Coef. (CS)	0.011	0.010	0.018	0.013	0.022	0.000	0.024	0.008	0.014	0.003
St. Error	(0.010)	(0.020)	(0.012)	(0.027)	(0.012)	(0.008)	(0.018)	(0.010)	(0.013)	(0.028)
p-val	0.237	0.627	0.154	0.637	0.080	0.993	0.173	0.385	0.283	0.914
Coef. (Poisson)	0.001	0.003	0.002	0.002	-0.001	0.001	0.001	0.004	0.000	0.002
St. Error	(0.003)	(0.004)	(0.003)	(0.004)	(0.003)	(0.002)	(0.004)	(0.002)	(0.003)	(0.006)
p-val	0.674	0.491	0.440	0.731	0.633	0.473	0.817	0.071	0.898	0.770
n (CS)	26,570	26,468	26,550	26,309	26,569	26,569	26,570	26,551	26,570	26,096
n (Poisson)	26,805	26,704	26,785	26,539	26,804	26,804	26,805	26,786	26,805	26,328
DV Mean	63.0	10.9	21.3	17.4	12.5	32.1	30.9	13.4	40.4	9.2

Note: Refer to note under Table B3.

B.3 Descriptive Statistics: Taxonomic Orders

Table B5: Bird Orders Present in US Lower-48 (2000-2020)

Order	**Species**	**No. Reported/Yr.**	**Examples**
Accipitriformes	39	9,981	Eagles, Hawks, Kites, Osprey, Vultures
Anseriformes	107	18,714	Ducks, Geese, Swans
Charadriiformes	150	9,484	Auks, Avocets, Curlews, Gulls, Jacanas, Oystercatchers, Plovers, Sandpipers, Skimmers, Skuas, Snipes, Stilts, Terns
Columbiformes	17	4,010	Pigeons, Doves
Coraciiformes	4	1,289	Kingfishers
Falconiformes	14	2,690	Falcons
Galliformes	32	2,505	Pheasants, Quail
Gruiformes	25	2,071	Coots, Crakes, Limpkin, Rails
Passeriformes	429	60,328	Blackbirds, Cardinals, Creepers, Crows, Finches, Flycatchers, Grassbirds, Jays, Larks, Nuthatches, Orioles, Shrikes, Sparrows, Starlings, Swallows, Tanagers, Thrushes, Tits, Vireos, Warblers, Wrens
Pelecaniformes	27	3,756	Bitterns, Herons, Ibises, Pelicans, Spoonbills
Piciformes	25	8,121	Woodpeckers
Podicipediformes	7	1,845	Grebes
Strigiformes	26	3,678	Owls
Suliformes	18	1,186	Anhingas, Cormorants, Frigatebirds, Gannets
Other Orders	103	1,048	Apodiformes, Caprimulgiformes, Ciconiiformes, Cuculiformes, Gaviiformes, Phaethontiformes, Phoenicopteriformes, Procellariiformes, Psittaciformes, Trogoniformes

Source: Audobon2022

B.4 Mediation Analysis: Human Population

Table B6: Mediation Analysis: Human Population

Effect of Shale Well Arrival on Human Pop.	
Coef (CS)	0.015
St. Error	(0.011)
p-val	0.180
n	31,357
DV Mean	149,792
Effect of Wind Turbine Arrival on Human Pop.	
Coef (CS)	-0.012
St. Error	(0.004)
p-val	0.003
n	31,062
DV Mean	292,627
Effect of Human Pop. on Birds Reported	
Coef (DID)	-0.062
St. Error	(0.080)
p-val	0.438
n	26,274
DV Mean	13,764

Note: Upper two panels report coefficient estimates, standard errors, and p-values, as well as sample sizes and baseline dependent variable means, for regression of human population in CBC circle's county on relative time indicators around the year of shale well or wind turbine arrival, using CALLAWAY2021200's *csdid* estimator, with year and circle fixed effects and a vector of covariates including (i) number of counters and (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count. Standard errors are clustered at the circle level, and continuous outcome is transformed using inverse hyperbolic sine function. Bottom panel reports the same statistics for regression of number of birds counted on human population using standard OLS difference-in-differences setup, with year and circle fixed effects and a vector of covariates including (i) number of counters and (ii) minimum and maximum temperature and maximum snowfall and wind speed in the circle on the day of the count. Standard errors are again clustered at the circle level, and continuous outcome and treatment are transformed using inverse hyperbolic sine function.

C Robustness Exercises

C.1 Poisson with Random Effects and Grid-Square Clustering

Figure C1: Poisson Model with Random Effects and Grid-Square Clustered Errors

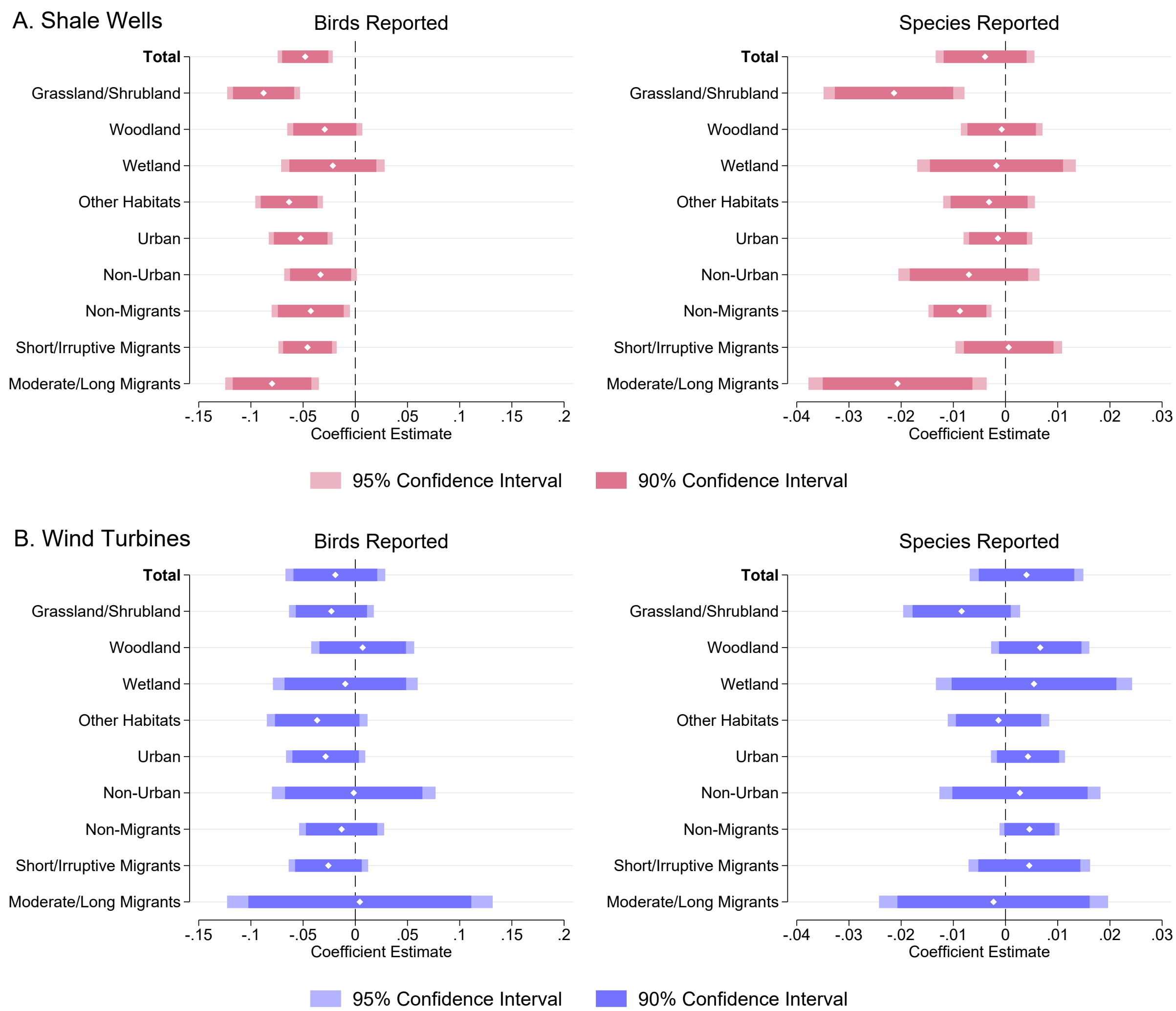


Figure reports results from specification analogous to Figure 4 – including year fixed effects and all the standard covariates – but with random circle effects and standard errors clustered at a 50km-by-50km grid square level to account for localized spatial correlation in outcomes.

C.2 Correlated Spatial Random Effects

Figure C2: Correlated Spatial Random Effects Model

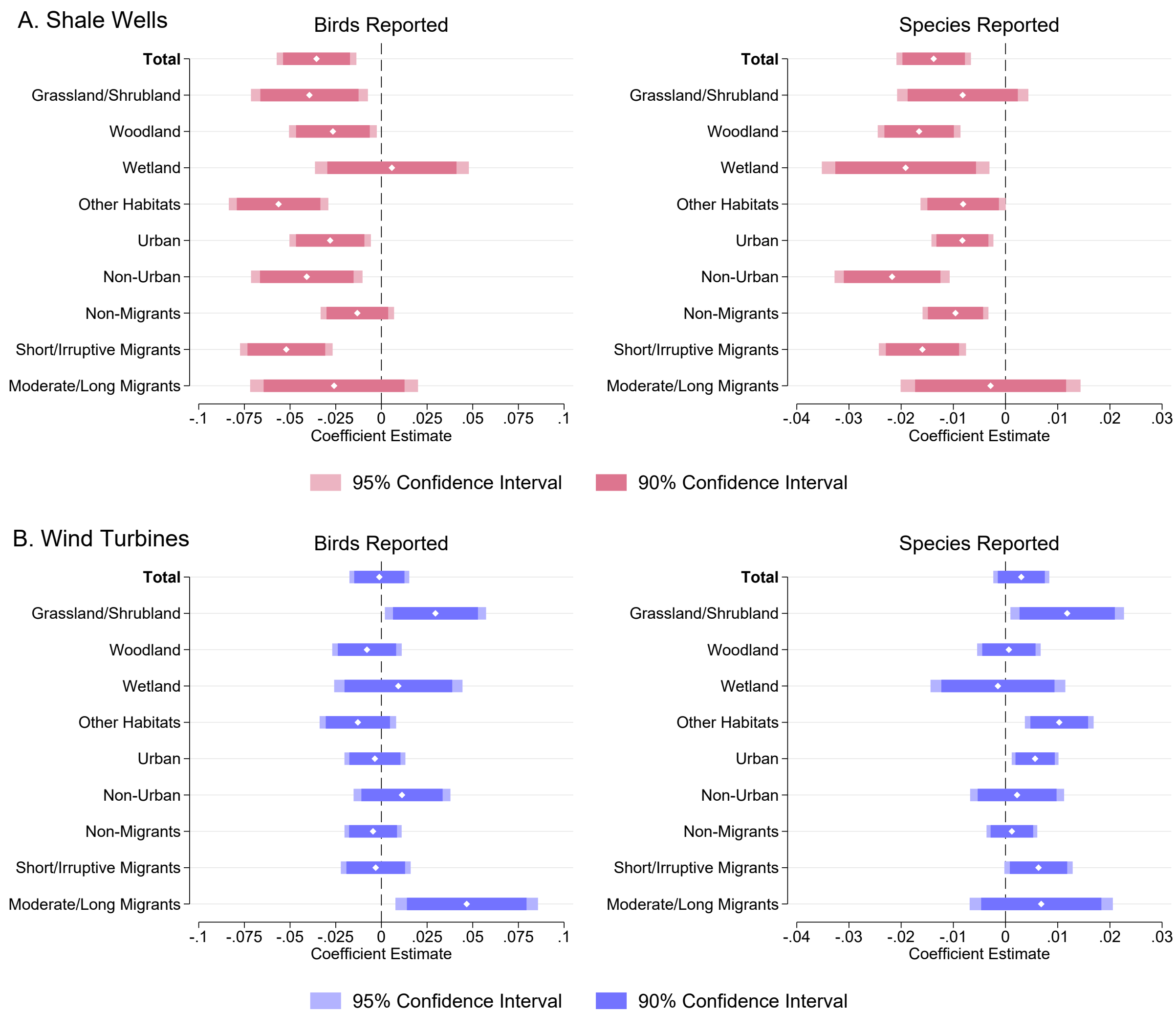


Figure reports results analogous to those described in Figure 4 – including year fixed effects and all the standard covariates – but using a correlated spatial random effects model based on a non-truncated inverse-distance weight matrix between CBC centroid points. The model includes spatial lags for the dependent variable and spatially lagged errors.

C.3 Difference-in-Differences with State-Year Fixed Effects

Figure C3: Difference-in-Differences (OLS) with State-Year Fixed Effects

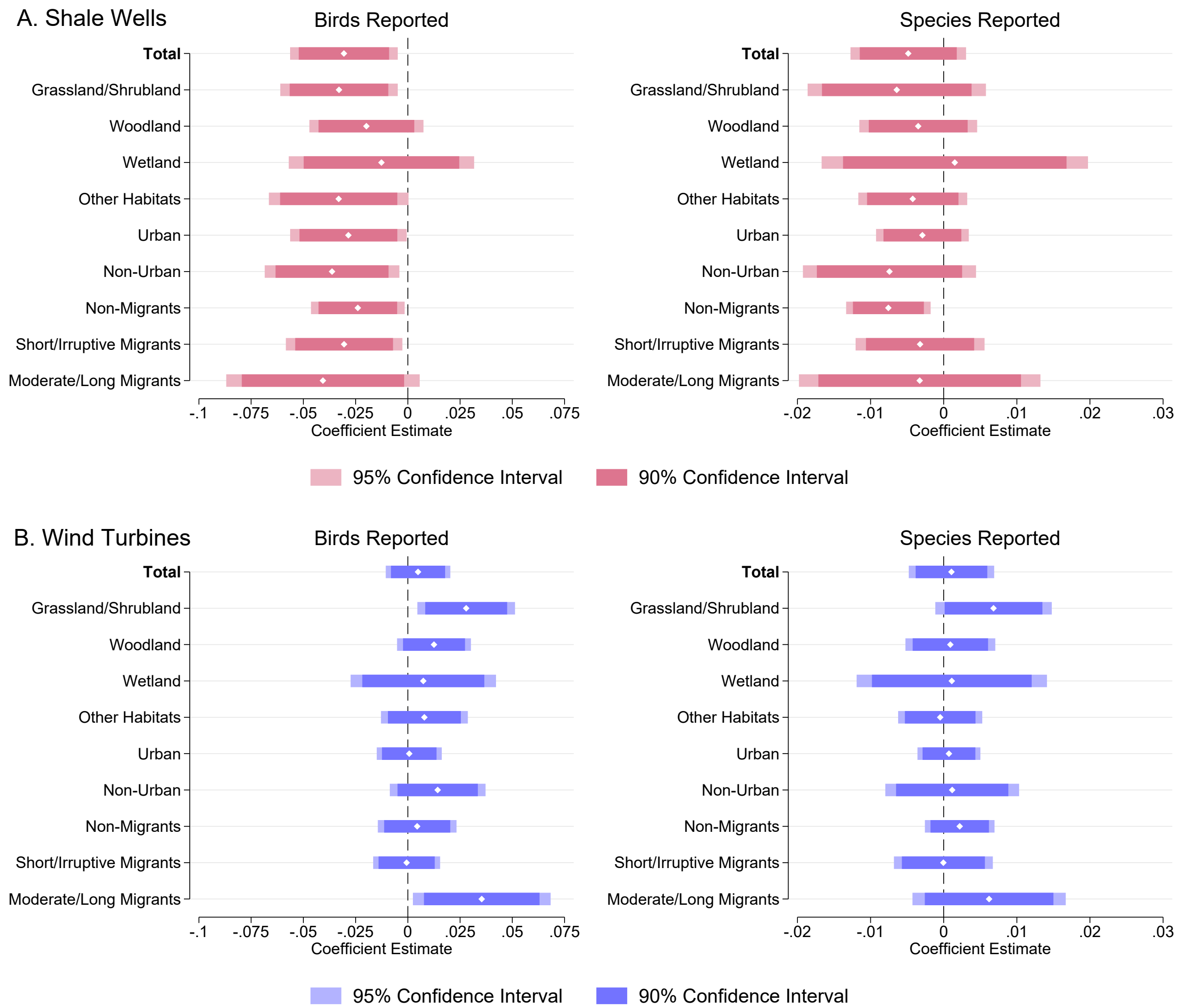


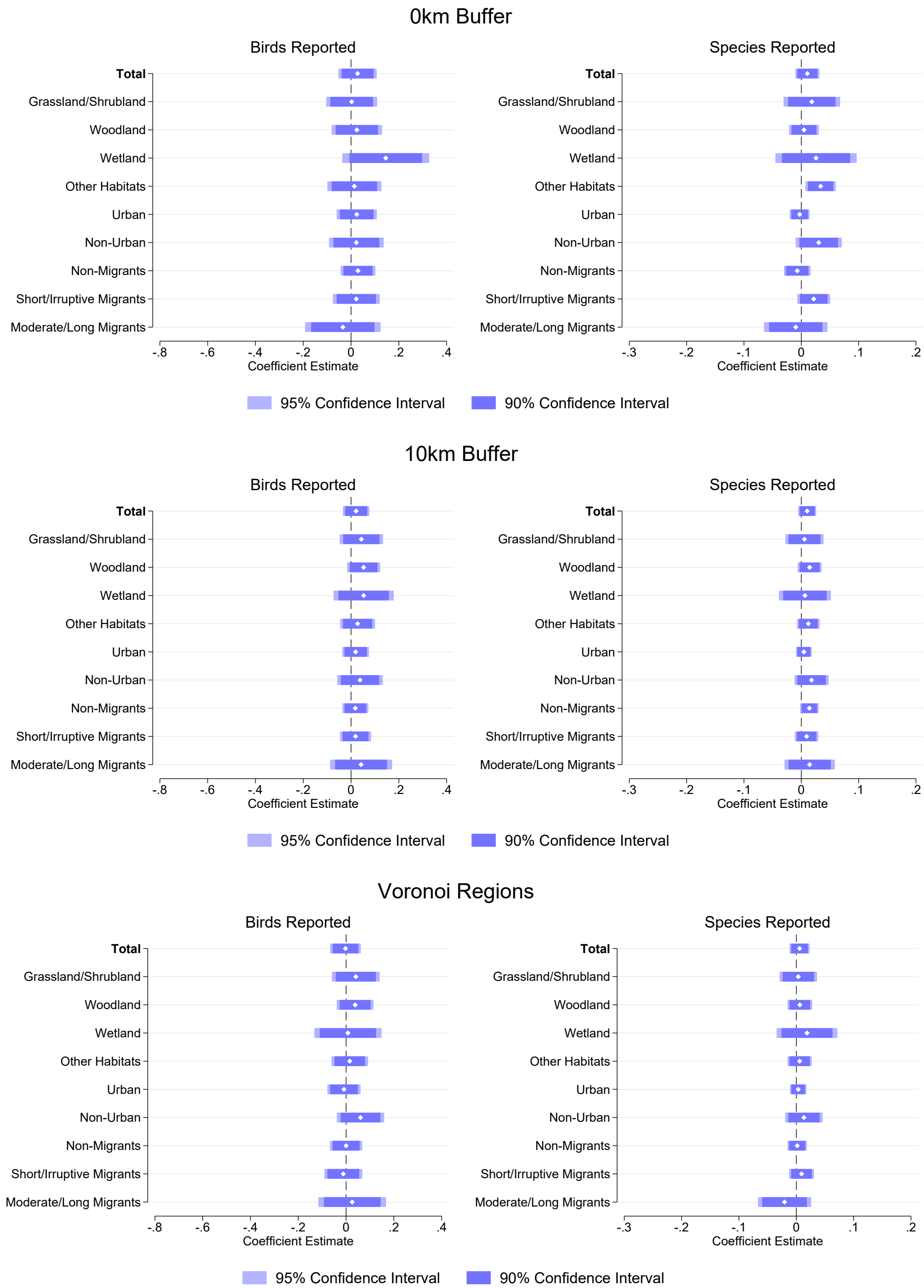
Figure reports results analogous to those in Figure 4, using the difference-in-differences specification defined in Equation 1, an OLS estimator, and continuous treatment definitions defined as the inverse hyperbolic sine of the cumulative number of shale wells or wind turbines operating within 5km of a CBC circle. I include circle and year fixed effects, the standard covariates, and clusters standard errors at the circle level. Additionally, this specification includes state-year fixed effects to account for potential state-level changes.

C.4 Alternative Buffer Zones

Figure C4: Shale Well Treatment: Robustness to Alternative Buffer Zones

Note: Figures are organized analogously to Figure 4. Top sub-figures use an alternative treatment definition wherein circles are treated in and after the year shale wells are first drilled within the strict boundaries of a CBC circle. This definition assumes no spillover effects from nearby shale wells. Middle figures use a treatment definition wherein circles are treated in and after the year shale wells are first drilled within a broader 10km buffer zone around the borders of a CBC circle. Bottom figures use a treatment definition wherein circles are treated in and after the year shale wells are first drilled within the Voronoi tessellation around a CBC circle centroid.

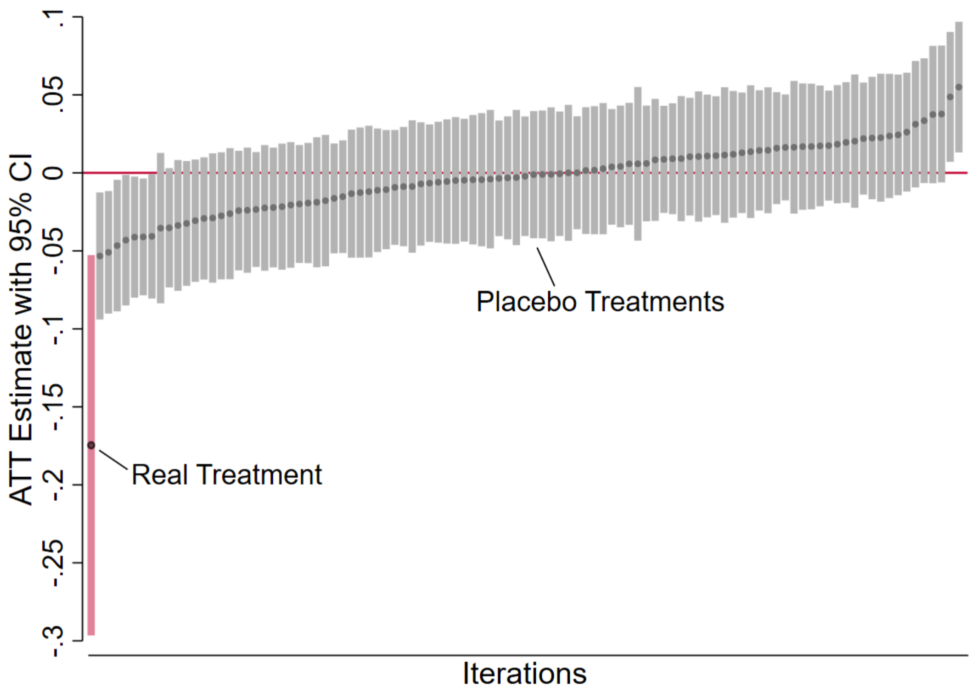
Figure C5: Wind Turbine Treatment: Robustness to Alternative Buffer Zones



Note: Figures are organized analogously to Figure 4. Top sub-figures use an alternative treatment definition wherein circles are treated in and after the year wind turbines are first constructed within the strict boundaries of a CBC circle. This definition assumes no spillover effects from nearby shale wells. Middle figures use a treatment definition wherein circles are treated in and after the year wind turbines are first constructed within a broader 10km buffer zone around the borders of a CBC circle. Bottom figures use a treatment definition wherein circles are treated in and after the year wind turbines are first constructed within the Voronoi tessellation around a CBC circle centroid.

C.5 Placebo Test

Figure C6: Placebo Test for Main Finding



Note: Placebo test for estimated effect of shale well arrival on subsequent total bird population counts. Model is specified and estimated as in Equation 1. 100 placebo treatments are assigned randomly to a share of CBC circles corresponding with the real treated share. This test assesses the likelihood that the preferred shale effect estimate could arise by random chance. Some significantly negative placebo estimates are to be expected, as some placebo treatments will include large numbers of truly treated units by chance.