Quantifying the Effects of Energy Infrastructure on Bird Populations and Biodiversity

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Abstract

Shale oil and gas production and wind energy generation both expanded rapidly across the United States between 2000-2020, raising concerns over impacts on wildlife. I combine longitudinal micro-data from the National Audubon Society's Christmas Bird Count with geolocated registries of all wind turbines and shale wells constructed in the contiguous US during this period to estimate the causal effects of these contrasting types of energy infrastructure on bird populations and biodiversity – key bellwethers of ecosystem health. Results show that the onset of shale oil and gas production reduces subsequent bird population counts by 15%, even after adjusting for location and year fixed effects, weather, counting effort, and anthropic land-use changes. Wind turbines do not have any measurable impact on bird counts. Negative effects of shale are larger when wells are drilled within important bird habitats.

Keywords: Shale Oil and Gas, Fracking, Wind Energy, Birds, Biodiversity

Synopsis: Expansion of wind turbines and fracking has raised concerns over impacts of energy infrastructure on wildlife. Using data covering the lower-48 United States, I find that fracking significantly reduces bird population counts, while wind turbines have no measurable effect on birds.

1 Introduction

Shale oil and gas drilling and construction of wind turbines for electricity generation have both expanded rapidly across large rural swathes of the United States in recent decades, and are likely to grow further in the future (EIA, 2022). Shale gas production in the US, which primarily relies on hydraulic fracturing, or "fracking," increased from 1.3 billion cubic feet in 2007 to 26.1 billion cubic feet in 2020 – a 20-fold increase (EIA, 2023). Onshore wind energy capacity in the United States grew from 2,539 megawatts in 2000 to 122,465 megawatts in 2020 – a 48-fold increase (Department of Energy, 2023) – and land-use for wind must grow by a further 4-7 times by 2050 to meet decarbonization targets (Net-Zero America, 2023). Numerous studies have explored the environmental impacts of these distinct energy land-uses (Black et al., 2021; Meng, 2017; Dai et al., 2015; Brittingham et al., 2014; Leung and Yang, 2012), but accurately quantifying their effects on wildlife at the population level has proven difficult (May et al., 2017).

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Shale oil and gas production creates significant ecosystem disturbances at both drilling and production stages (Jackson et al., 2014; Kiviat, 2013). These disturbances include air pollution, leakage and leaching of contaminated groundwater, surface spills, light and noise pollution, and generalized increases in human settlement and activity (Black et al., 2021). Fracking also substantially increases local road traffic, with resulting dust emissions reaching up to 180m into adjacent fields (Spiess et al., 2020). Focusing on Colorado, Northrup et al. (2015) document increased avoidance behavior among mule deer around fracking well pads, and Maguire and Papeş (2021) find that grassland bird species diversity declines as the number of shale wells increases. Analyzing grassland bird avoidance behavior around shale oil and gas extraction sites in North Dakota, Thompson et al. (2015) document avoidance behaviors within 150m of roads and 350m of wells. Given the scale of shale oil and gas production in affected areas, these avoidance zones multiply for sensitive species. Lifecycle assessments of shale oil and gas impacts on wildlife emphasize surface water disturbances during drilling – as fracking requires up to 60 million liters of water per well – and landscape fragmentation, which may disturb specialist birds while favoring generalists (Caldwell et al., 2022; Tagliaferri et al., 2015).

Wind energy installations introduce tall, dispersed structures with rotating turbines and transmission lines that may impact wildlife, particularly birds and bats, through a variety of mechanisms. In a meta-study of wind energy's effects on birds, Schuster et al. (2015) point to evidence of avoidance behavior during turbine construction and around active turbines, and note that impacts depend on bird and site characteristics – with collision risk and other negative effects larger for migrant or commuter species and in previously undisturbed habitats (Kiesecker et al., 2011). In a case study of three sites in North and South Dakota, Shaffer and Buhl (2015) document avoidance behaviors in 7 of 9 grassland bird species up to 300m around wind turbines, with effects persisting up to five years after turbine construction. Recent lifecycle assessments of wind turbine impacts on wildlife have emphasized global modeling approaches that overlay wind installations onto species distribution maps to assess potential habitat loss and collision and disturbance risks (May et al., 2020; Laranjeiro et al., 2018). One study of this kind found that wind energy installations in Norway were inefficiently located with respect to bird habitats, putting seabirds, raptors, and waterfowl at greatest risk (May et al., 2021). Piasecka et al. (2019) assess the lifecycle impacts of onshore versus offshore wind installations in Poland and find onshore installations have significantly larger environmental impacts over installation and operational phases.

Estimates of global impacts of fracking and wind energy installations on birds are based overwhelmingly on theoretical models or single- or multi-site case studies, which are then extrapolated (e.g., Barton et al., 2016). Loss et al. (2013) synthesize extrapolation studies of wind energy effects and conclude that approximately 234,000 birds are killed annually in wind turbine collisions in the US. However, the authors acknowledge substantial imprecision in this approach, as site-specific studies often lack external validity, and studies focused purely on fatalities may miss avoidance effects. Presenting an alternative, population-level approach, Miao et al. (2019) use spatial longitudinal data on wind installations and bird observation routes to estimate wind turbine impacts on bird populations, finding small negative effects. Likewise, van der Burg et al. (2023) focus on the effects of oil and gas and biofuel crop production on four grassland bird species in North Dakota. Aggregating from site-specific to circle-year level bird counts and applying a Poisson modeling approach, the authors find that both oil and gas and biofuel crops lead to distributional shifts in bird populations away from these disturbances, with the effects of biofuels dominating.

This paper builds on these population-level approaches by using longitudinal, geolocated bird censuses conducted each December through the National Audubon Society's Annual Christmas Bird Count (CBC) (National Audubon Society, 2022). I draw on CBC data covering the entire lower-48 United States between 2000 and 2020. The Christmas Bird Count is one of the largest and longest-running citizen science projects in the world, and represents a uniquely rich source of data on bird population and species dynamics (McCaffrey, 2005). CBC data have previously been used to estimate region-specific bird population trends (Soykan et al., 2016) and to measure bird losses after the Deepwater Horizon oil spill (Haney et al., 2014). I overlay CBC data with complete geolocated registries of wind turbine installations and shale oil and gas wells drilled over the 2000 to 2020 period, provided by the United States Geological Survey (US Geological Survey, 2022) and Rystad Energy (Rystad Energy, 2022), respectively. I then separately estimate difference-in-differences specifications around the year of arrival of (i) shale wells or (ii) wind turbines within the vicinity of a CBC count location to estimate the effects of each of these distinct energy infrastructures on bird populations and species diversity.

This study advances research on population-level wildlife impacts of energy technologies along several dimensions. First, I estimate comparable effects for two distinct types of energy infrastructure using a common data structure and methodology. Second, I estimate effects for the entire lower-48 United States over a twenty-year period covering major expansions in shale oil and gas production and wind energy. Third, I explore important sources of effect heterogeneity, including bird characteristics, taxonomic orders, and proximity to important habitats. Fourth, I implement a cutting-edge statistical estimator to avoid potentially serious biases inherent to standard fixed effects models (Goodman-Bacon, 2021). Results enable data-driven calibration of global lifecycle assessment models, such as in May et al. (2020).

2 Economic and Environmental Impacts of Birds

Birds provide important economic benefits, particularly for rural communities. The U.S. Fish and Wildlife Service (2016a) estimates that 45.1 million people participated in birdwatching activities in the United States in 2016 (representing 18% of the US population), with 16.3 million making specific trips for this purpose. Birdwatching activities in this year led to US$39.2 billion in expenditures, supporting 782,000 direct and indirect jobs and generating US$16.2 billion in state and federal tax revenues. A further 2.4 million US residents participated in bird hunting activities, resulting in US$2.3 billion in expenditures across 15 million individual trips. Birdwatchers and hunters have above-average spending power, increasing their contributions to rural economic activity (U.S. Fish and Wildlife Service, 2016b).

Birds are also indicators of broader environmental health and provide extensive ecosystem services (Fraixedas et al., 2020). These include pest and disease control (Frank and Sudarshan, 2023; Markandya et al., 2008), pollination, seed dispersion, and regulation of forest and wetland health (Gaston, 2022; Whelan et al., 2008). Conservation of grasslands – where much of the expansions in shale oil and gas production and wind energy generation have occurred – also has significant economic benefits for beekeepers, with downstream benefits for agriculture (Otto et al., 2022). Contingent valuation studies have documented positive willingness-to-pay for bird conservation in Sweden (Kataria, 2009) and for biodiversity conservation in the United States (Jacobsen and Hanley, 2009), while hedonic pricing studies have estimated substantial property-value premiums for proximity to a wildlife refuge (Neumann et al., 2009).

3 Methods

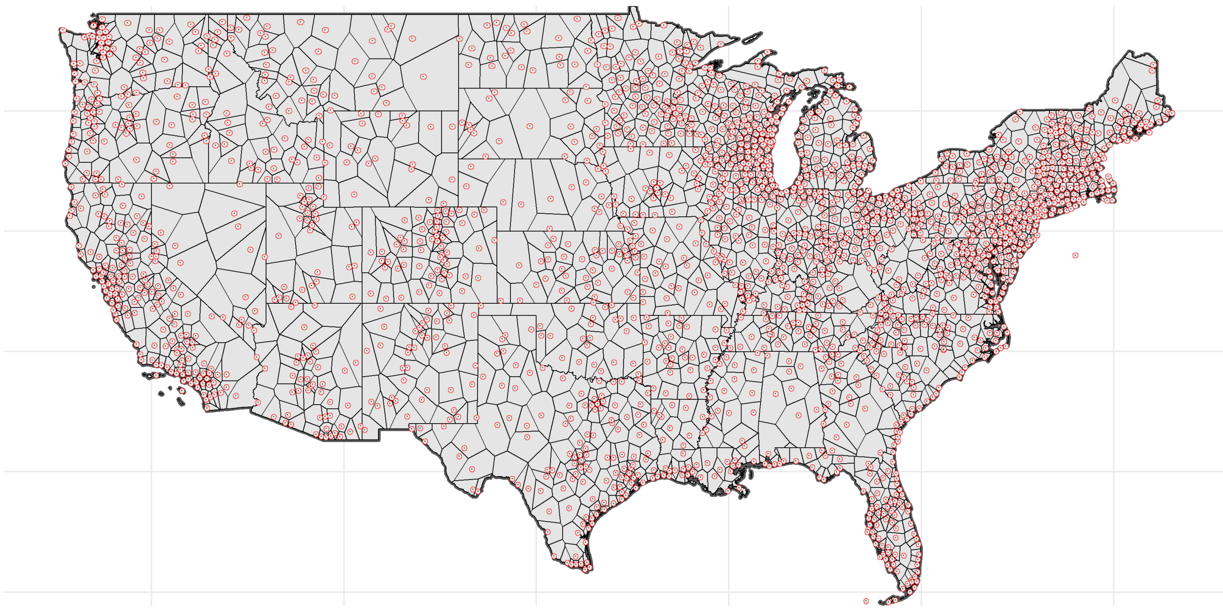
Data

I draw longitudinal data on bird population and species counts from the National Audubon Society's Annual Christmas Bird Count (CBC) (National Audubon Society, 2022). The CBC is conducted annually on a day between December 14th and January 5th, and consists of volunteers, led by an experienced organizer, canvassing segments of a 24.1km (15 miles) diameter circle. Participants record the number of each species of bird they observe, and temperature, snowfall, wind-speed, number of participants, and mode of observation (e.g., at a feeder, walking, by car, etc.) are also reported. Circles are subdivided into units, and volunteers' routes are carefully coordinated within each unit to maximize coverage across the circle while minimizing double-counting. Critically, CBC methodology and (in almost all cases) circle locations remained unchanged over the study period. Appendix Figures A1 and A2 provide a diagram and example of CBC circles and counting procedures.

The Christmas Bird Count presents several advantages over self-reported bird datasets with national coverage, such as eBird, including: (i) its stable and transparent methodology, which allows adjustment for counting effort and avoids endogenous changes in birders' choice of where to observe and report, and (ii) its reporting of bird population numbers at the species level. In contrast, eBird posters do not typically report number observed for each species, and may under-report common species and over-report remarkable species (Hochachka et al., 2021). The CBC has the limitation of only reporting counts from a single day in December, thus missing birds that are not present in the winter. While this limitation leads the CBC to under-count each area's true bird numbers and biodiversity throughout the year, it does not compromise causal inference, as identification comes from comparisons *within* circles over time. While measurement errors may occur in CBC counts (e.g., mis-identification of species, duplicate counts, missed birds), there is no evidence to suggest that these errors varied systematically across years or circles. To avoid possible over-counting errors in cases where very large round numbers of birds were reported, I winsorize population counts at the 99th percentile; results are robust to not winsorizing.

Figure 1 presents a map of CBC circles for the lower-48 United States, as well as Voronoi tesselations corresponding to each circle. Figure 2 maps bird population and species counts based on CBC data averaged over 2000-2020. Winter bird populations are most dense in California, along the Gulf and East Coasts, and in the southern Midwest and east central South. Species diversity is highest along the coasts.

Figure 1: Christmas Bird Count Locations within Voronoi Tessellations

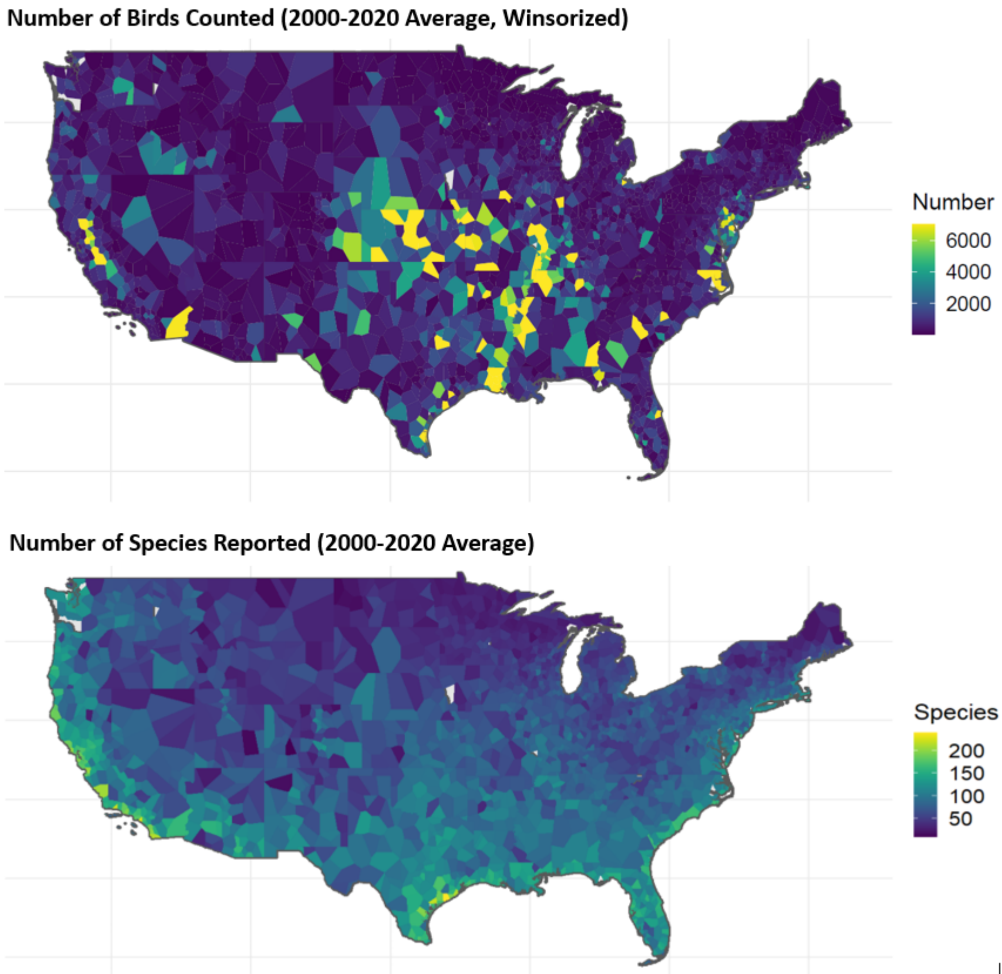


Note: CBC circles for the lower-48 United States with Voronoi tesselations corresponding to each circle. Voronoi tesselations subdivide a plane into mutually exclusive regions around a set of points, $\mathbf{P}$, wherein all points in a region are nearer to point $\mathbf{p} \in \mathbf{P}$ than to any other point in $\mathbf{P}$. Dividing the lower-48 US around CBC circle centroids in this way creates a map with comprehensive national coverage, under the assumption that each surveyed CBC circle is representative of its Voronoi region.

Data on shale oil and gas wells are drawn from Rystad Energy's U-Cube Platform. Rystad Energy is a proprietary data provider for the oil and gas industry (Rystad Energy, 2022). Geolocated data are reported at the shale field level for the entire United States over the 2000-2020 period, and include number of wells completed in each field each year, as well as oil-equivalent production at the field-level. The dataset provides comprehensive coverage of over 240,000 wells across 5,414 fields. Wind turbine data are drawn from the US Wind Turbine Database, a joint initiative of the US Geological Survey, the US Department of Energy, and other partners (US Geological Survey, 2022). The dataset contains the geolocation and date of construction for every commercial wind turbine project in the US over the 2000-2020 period, with coverage of over 115,000 turbines. Figure 3 maps the geographic and chronological spread of shale oil and gas fields and wind turbines across the lower-48 United States between 2000 and 2020.

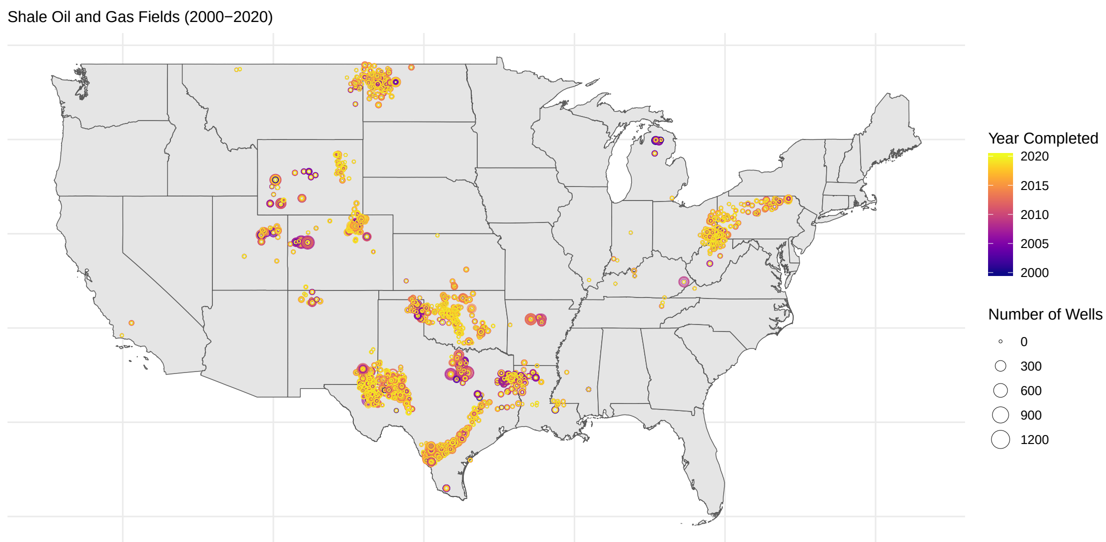
To explore causal mechanisms and effect heterogeneity, I supplement these datasets with data on annual county-level human population (National Cancer Institute, 2022), spatial data on important bird areas (National Audubon Society, 2023), and data on bird characteristics (Soykan et al., 2016). To control for changes in anthropic land use over time (i.e., agriculture, pasture, and developed uses), I clip spatial raster data from the National Land Cover Database (NLCD) (US Geological Survey, 2023) – which is available in 2001, 2004, 2006, 2008, 2011, 2013, 2016, and 2019 – to the boundaries of each CBC circle and compute the share of circle area occupied by each of these anthropic land-uses.

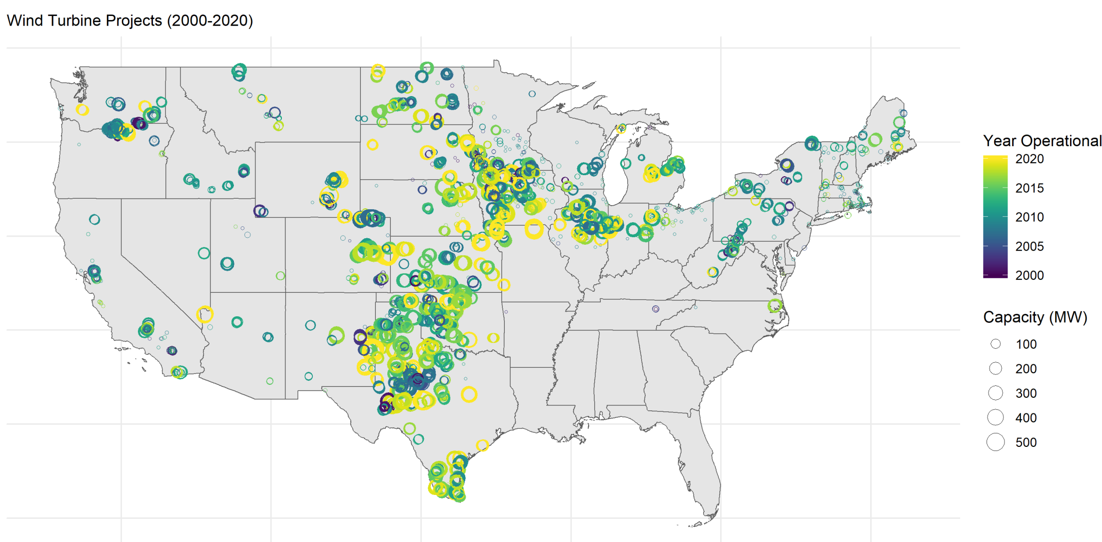
Figure 2: Bird Population and Biodiversity Counts, December (2000-2020 Average)



Source: National Audubon Society (2022)

Figure 3: Shale Oil and Gas and Wind Energy Expansion (2000-2020)





Source: Rystad Energy (2022) and US Geological Survey (2022)

Econometric Strategy

To identify CBC circles that are treated by the arrival of shale wells or wind turbines, I overlay geolocated well and turbine registries onto the circles map to detect if and when wells or turbines are constructed in proximity to a circle (i.e., within 5km of the circle boundary – see Appendix Figure A1 for an illustration). I include the 5km buffer to allow for spillover effects from shale or wind installations that are nearby, but not inside, a circle. To test sensitivity of results to this definition of treatment, I estimate robustness tests using (i) no spillover buffer, (ii) an alternative 10km buffer, and (iii) larger Voronoi regions around each circle (as explained in Figure 1). Appendix Figure A3 plots the percentage of CBC circles treated over time using these alternative definitions.

I define outcome y_{ct} as the number of birds counted, or number of species counted, in circle c in year t, where y_{ct} measures either total number or species counted, or number or species counted for a particular bird type (e.g., grassland, urban, migrant, etc.) or taxonomic order (e.g., *Accipitriformes, Passeriformes*).

To estimate the effect of construction of shale wells or wind turbines near a CBC circle on subsequent counts, I implement a pre/post difference-in-differences specification (Wooldridge, 2010), wherein I regress outcomes of interest on a treatment indicator T_{ct}, which assumes a value of 1 beginning in the period when (i) wells were completed, or (ii) turbines were constructed in proximity to circle c, and assumes a value of 0 otherwise. I include a vector of circle-year covariates, $\mathbf{X}_{ct}$, including weather (minimum and maximum temperature and maximum snowfall and wind speed in circle c on the day of the count), counting effort (number of counters participating), and the proportions of circle area under agricultural, pasture, and developed land-uses, as well as circle and year fixed effects, γ_c and δ_t, which absorb time-invariant variation (including unobservables) at the circle level and yearly variation affecting all circles:

$$y_{ct} = \beta_1 T_{ct} + \mathbf{X}'_{ct}\beta_2 + \gamma_c + \delta_t + \epsilon_{ct} \tag{1}$$

I cluster standard errors at the level of treatment (i.e., circle-level) (Abadie et al., 2022) and transform continuous outcomes using the inverse hyperbolic sine function, which reduces the influence of extreme values without dropping zero-value outcomes (Bellemare and Wichman, 2019). I estimate Equation 1 using the *csdid* estimator developed by Callaway and Sant'Anna (2021), which appropriately weights group-time comparisons to avoid bias introduced by comparing treated units with units that have already been treated (Goodman-Bacon, 2021). This is particularly important since wells and turbines arrived in CBC circles at different times and may exert heterogeneous effects depending on place and time. I estimate the model separately for shale wells and wind turbines.

There is a trade-off between the binary pre/post treatment indicator, which allows implementation of Callaway and Sant'Anna (2021)'s *csdid* estimator, and continuous treatment measures (e.g., number of wells or turbines), which allow estimation of marginal treatment effects but are not compatible with modern staggered treatment estimators. Thus, I additionally estimate an equation analogous to Equation 1 using a Poisson model for untransformed count data and continuous versions of T_{ct}, defined as the inverse hyperbolic sine of the cumulative number of shale wells or turbines operating in proximity to a CBC circle. I discuss results from both estimators in section 3.

Causal inference with this empirical strategy is supported by several arguments. First, CBC bird counts use a systematic, stable, common methodology across the study period, avoiding concerns over endogenous changes in birding effort that plague analyses relying on self-reported bird data. Second, inclusion of circle and year fixed effects and weather and effort covariates substantially reduces omitted variable bias. Controlling for time-varying NLCD data on anthropic land uses within each circle accounts for possible confounding factors associated with the expansion of other human activities, including biofuel feedstock production, air pollution, and pesticide use. Third, geographical spacing between circles reduces the scope for spillovers between treated and control units. Fourth, causal inference using difference-in-differences requires that the parallel pre-trend assumption hold. I test for pre-trend differences explicitly in Appendix Figures A5-A6 using event studies based on the *csdid* estimator around year of first well or turbine arrival, and find they are statistically insignificant.

4 Results

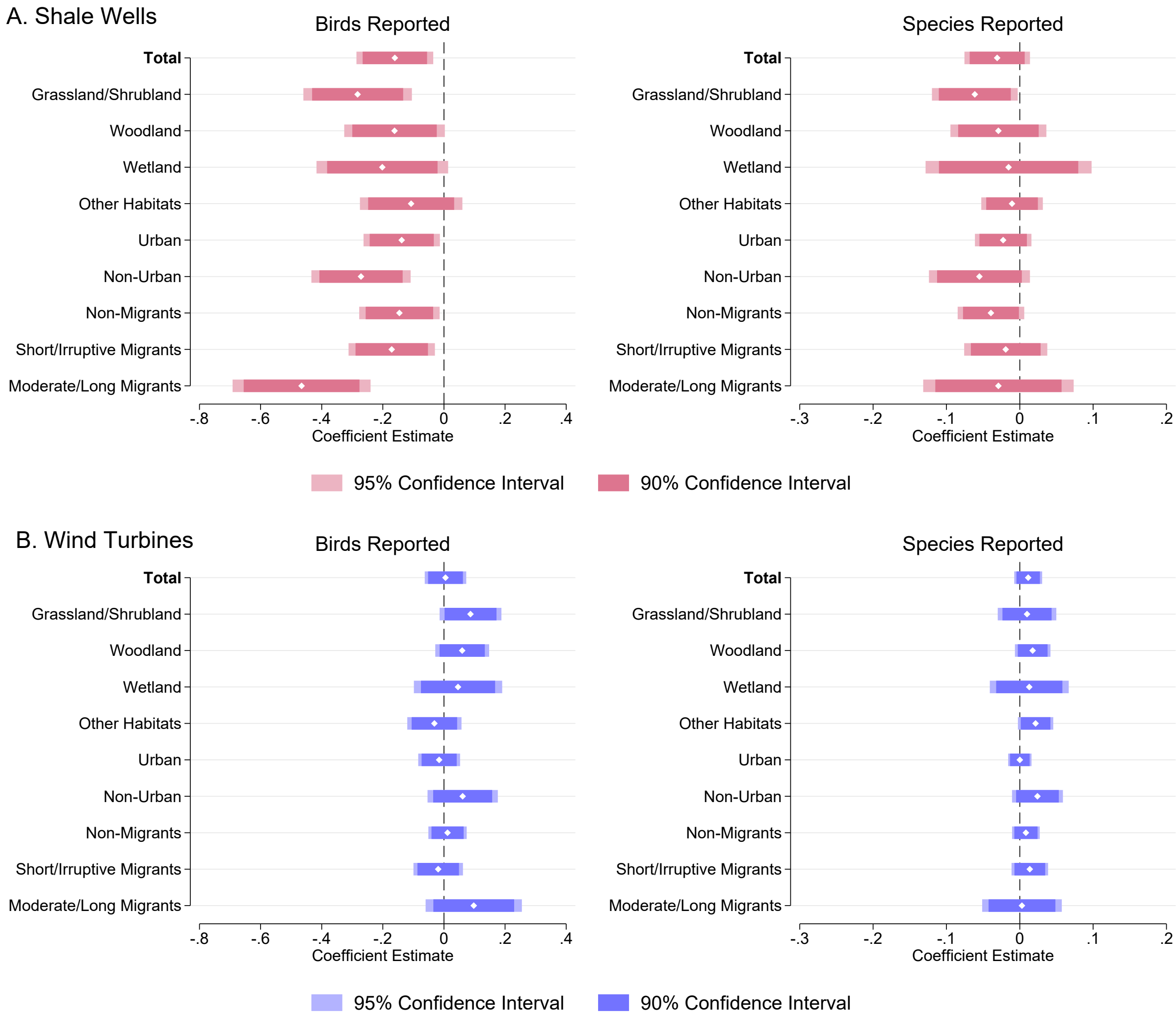
Effects of Shale Oil and Gas Production

Figure 4 reports coefficient estimates with 90% and 95% confidence intervals for the effect of (4A) shale well arrival and (4B) wind turbine arrival within 5km of a CBC circle on bird population and species counts. Corresponding results and sample statistics are reported in Appendix Tables A1-A4. In Section 5, I estimate a variety of robustness checks for these results using alternative models and treatment definitions.

Arrival of shale wells within 5km of a CBC circle reduces the total number of birds counted in subsequent years by 15% (p = 0.008). Since outcomes are transformed using the inverse hyperbolic sine function, semi-elasticities may be interpreted as the percentage change in number or species of birds counted after arrival of shale wells or wind turbines near a CBC circle. Semi-elasticities may be computed as: $100 \times (e^{(\beta_1)} - 1)$, which in the case of total birds reported, is: $100 \times (e^{(-0.161)} - 1) = -15\%$ (Bellemare and Wichman, 2019). Effects of well arrival are most negative for moderate to long migrants (-37%, $p < 0.001$), non-urban birds (-23%, p = 0.001), and grassland and shrubland birds (-24%, p = 0.001). Arrival of shale wells near a CBC circle does not have a statistically significant effect on total species counts, but reduces grassland and shrubland species diversity by 6% (p = 0.040) and weakly reduces species diversity among non-migrants by 4% (p = 0.090). Across all characteristics, point estimates of shale effects on bird counts are negative.

Results for the continuous treatment definition (i.e., number of shale wells operating in proximity to a CBC circle) using a Poisson model and untransformed count data, reported in Appendix Figure A7, are similar: a 10% increase in number of wells reduces total bird population count by 0.26% (p = 0.008), which equates to a reduction of 3.64 birds per well drilled – based on a baseline (year 2000) average total bird count of 8,253 and an average of 59 shale wells per treated circle. A 10% increase in wells reduces the number of medium-to-long migrant birds by 0.6% ($p < 0.001$), grassland birds by 0.5% (p = 0.002), and resident birds by 0.3% (p = 0.020). The Poisson model of species diversity with continuous treatment predicts *larger* negative effects of shale on species diversity, relative to *csdid*: a 10% increase in wells weakly reduces the total number of species reported by 0.07% (p = 0.085), and significantly reduces the number of medium-to-long migrant species reported by 0.18% (p =

Figure 4: Effects of Shale Well and Wind Turbine Arrival on Bird and Species Counts (Disaggregated by Characteristic)



Effects of (A) Shale Well and (B) Wind Turbine Arrival on Bird and Species Counts. Figures report 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 shale wells were first drilled or wind turbines were first constructed 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, (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.

0.015), grassland/shrubland species by 0.15% (p = 0.004), non-urban species by 0.1% (p = 0.075), and resident species by 0.1% ($p < 0.001$). Again, all point estimates for shale well effects on population and species counts are negative.

Analogous results disaggregated by taxonomic order are presented in Appendix Figure A8. Effects of shale oil and gas well arrival on bird populations are significantly negative for *Strigiformes* (owls), *Piciformes* (woodpeckers), *Falconiformes* (falcons), *Pelecaniformes* (e.g., bitterns, herons, pelicans), *Accipitriformes* (e.g., hawks, eagles, vultures), and *Passeriformes* (i.e., perching birds), while well arrival has no measurable effect on *Charadriiformes* (e.g., shorebirds), *Anseriformes* (ducks, geese, and swans), and *Columbiformes* (pigeons and doves). Shale well arrival significantly reduces the number of *Strigiformes* species counted. More detailed description of bird orders is presented in Appendix Table A5. The finding of large negative effects for grassland/shrubland birds, non-urban birds, and moderate-to-long migrants aligns with previous findings that shale oil and gas expansions have occurred largely in grassland ecosystems, with disruptive effects on migratory birds, habitat specialists, and species that are sensitive to human activities (Thompson et al., 2015).

Effects of Wind Energy Installations

Arrival of wind turbines within 5km~~.~~ of a CBC circle has no measurable effect on total bird population or species counts (Figure 4B), nor does it have a measurable effect when results are disaggregated by characteristic or taxonomic order (Appendix Figure A9). Null effect estimates are quite precise: the 95% confidence interval for turbine effects on total population counts ranges from -0.063 to 0.073; the confidence interval for total species counts ranges from -0.008 to 0.031. Turning to the continuous treatment definition (i.e., number of turbines operating near a CBC circle), estimated effects on bird and species counts are again statistically indistinguishable from zero at the circle-level – though this could mask smaller or highly-localized effects that this empirical strategy is not powered to detect.

5 Robustness and Model Sensitivity

In this section, I evaluate the sensitivity of findings to alternative estimators, empirical specifications, and sample definitions.

Poisson Count Model with Random Effects and Grid-Square Clustering

To test the sensitivity of the continuous treatment effect estimates, I re-estimate the Poisson count model with random effects and standard errors clustered at a broader 50km-by-50km grid-square level – thus accounting for spatial correlation in outcomes. Results, reported in Appendix Figure A10, again show significant negative effects of shale on the number of birds reported (total and across nearly all characteristics), as well as negative effects of shale on the number of grassland and moderate-to-long migrant species reported; estimated effects of wind turbines remain statistically insignificant.

Correlated Spatial Random Effects Model

To more fully account for spatial and temporal correlations in the CBC data, I estimate a correlated spatial random effects model, including annual fixed effects and all the standard control variables. I allow for spatial lags in the dependent variable and spatially lagged errors using an inverse distance spatial matrix between CBC centroid points. Reported in Appendix Figure A11, results show significant negative effects of shale oil and gas wells on the total number of birds reported and across most characteristic types, as well as significant negative effects on the total number of species and most species characteristics reported. Effects of wind turbines remain mostly insignificant, with the exception of small *positive* effects on some characteristic types.

Difference-in-Differences (OLS) with State-Year Fixed Effects
To account for potential region-level confounding factors that could affect birds (e.g., changes in state policies or state-level trends), I re-estimate the continuous treatment version of Equation 1 using OLS and including state-by-year fixed effects alongside the standard circle and year fixed effects and controls. Results, reported in Appendix Figure A12, again show significant negative effects of shale wells on number of birds reported, and smaller and insignificant effects of wind turbines.

Alternative Buffer Zones Around CBC Circles
I assess sensitivity to alternative buffer zones around CBC circles by re-estimating my preferred specification (which used a 5km buffer to account for localized spillovers) with a 0km buffer, a 10km buffer, and larger Voronoi regions around each circle. Results, reported in Appendix Figures A13 and A14, remain mostly unchanged.

Placebo Test
Finally, I assess whether one of the main results – the significant negative effect of shale oil and gas on total bird population counts – could have been spurious, using a placebo test. Specifically, I re-estimate Equation 1 using the preferred specification for 100 placebo treatments, which are assigned randomly to a share of CBC circles corresponding with the real treated share. Results, reported in Appendix Figure A15, show that the real treatment effect estimate is a clear outlier relative to placebo estimates, indicating that this effect is not the result of random coincidence between shale infrastructure and bird population declines.

Additional Event Studies for Key Outcomes
To further assess the validity of the identifying parallel pre-trends assumption, I report additional event studies based on the preferred *csdid* estimator in Appendix Figure A16. For brevity, I report results for shale effects on the number of birds reported for key characteristic groups: grassland/shrubland, non-urban, short/irruptive migrants, and medium/long migrants. Results confirm that, prior to shale well arrival, CBC circles treated by shale wells were on comparable trajectories to non-treated circles, but experienced significant declines in the number of birds counted in post-treatment years.

6 Testing Mechanisms

Changes in Human Population
What factors underlie the significant negative effects of shale wells on birds? Motivated by evidence that fracking booms increase human in-migration to affected regions (Wilson, 2022), I test whether shale oil and gas production or wind energy installations lead to increased human population within CBC circles, which could in turn exert negative effects on birds independently of direct energy land-use impacts. First, I regress human population within a circle's county on well or turbine arrival in proximity to a CBC circle, analogously to Equation 1. Next, I regress number of birds reported on human population using a continuous

difference-in-differences specification to assess whether increased human activity affects bird counts. Results, presented in Appendix Table A6, suggest that neither shale oil and gas nor wind turbine arrival have measurable effects on human population levels within affected CBC circles. Further, increases in human population have no statistically significant effect on the number of birds counted. These findings suggest that negative effects of shale oil and gas production come not from increased human settlement in affected areas, but rather from factors intrinsic to shale oil and gas drilling, production, and transportation processes.

Proximity to Important Bird Habitats

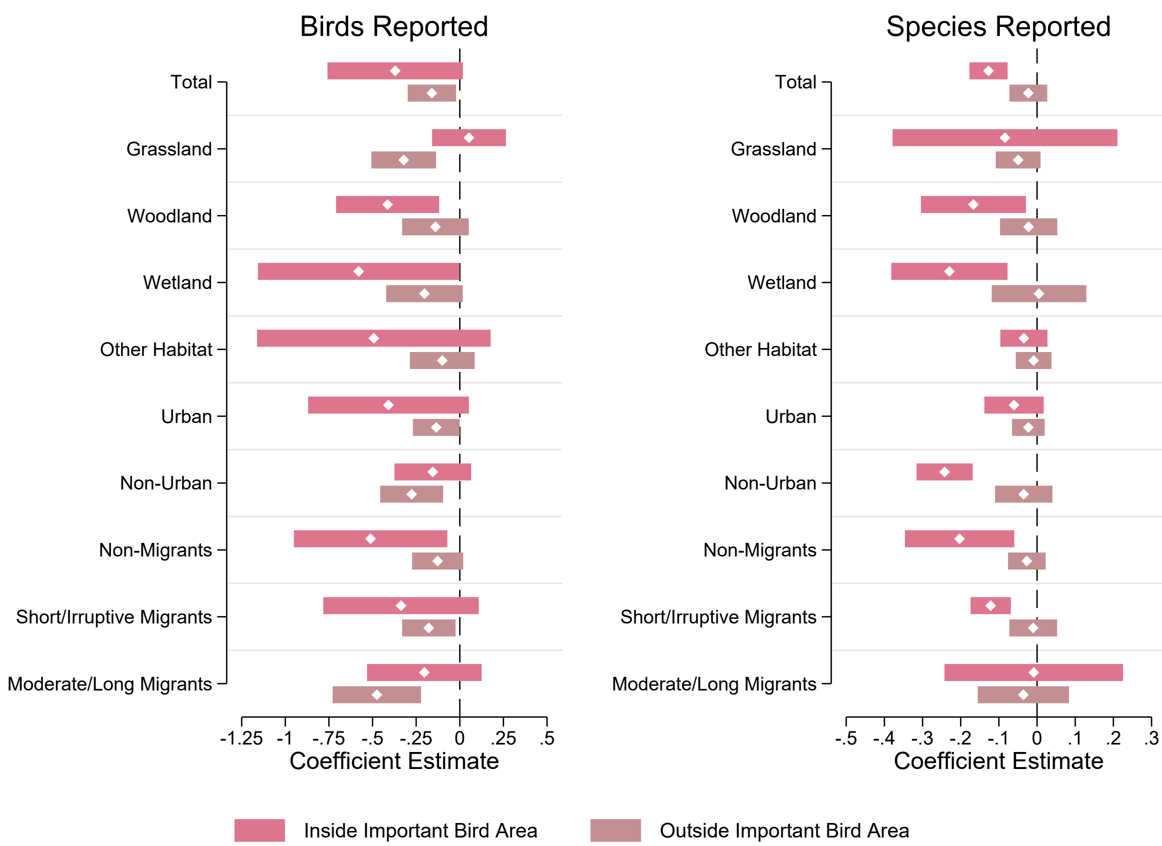
I explore heterogeneity in effects inside and outside important bird areas to assess whether disruption of sensitive habitats may underlie the negative impacts of shale. Important bird areas are defined by the National Audubon Society (2023) and mapped in Appendix Figure A17. Results, presented in Figure 5, suggest negative effects of shale oil and gas production on bird population counts are larger for CBC circles located inside sensitive habitats, though the relatively small number of these locations means estimates become less precise. Effects of shale well arrival on total species diversity – as well as species counts for woodland, wetland, non-urban, non-migrant, and short/irruptive migrant birds – become significantly negative and of larger magnitude when focusing on CBC circles located inside important bird areas. Analogous results for wind turbine arrival are presented in Appendix Figure A18. Estimation of zero effects of turbine arrival on bird populations does not change when focusing inside or outside important bird areas. Effects of wind turbines on species diversity are zero outside important bird areas, and zero or positive within important bird areas.

7 Discussion

Debate over energy infrastructure impacts on birds has been dominated by discussion of wind turbines, with 173 stories in major US news outlets reporting on this topic in 2020 (International Newsstream Database, 2023). In contrast, only 46 news stories discussed the effects of shale oil and gas or fracking on birds in the same year (Appendix Figure A4). Despite this focus on wind turbines in public discourse, I find no measurable effect of wind energy installations on bird population counts or species diversity at the circle-level. In contrast, I find that the onset of shale oil and gas production exerts significant negative effects on bird population counts, as well as significant negative effects on counts of bird species diversity when wells are drilled inside important bird habitats.

An important caveat to these findings is that surveys such as the CBC aggregate site-specific observations to circle-level counts, leaving lower-level variation unrecoverable (van der Burg et al., 2023). The present study is therefore unable to detect localized avoidance behaviors such as those measured in Shaffer and Buhl (2015), and lacks the statistical precision to identify small numbers of collision deaths, such as those counted in Loss et al. (2013). Nevertheless, it is noteworthy that the same empirical strategy that fails to detect significant effects of wind turbines on birds at the circle-level nevertheless detects significant and robust negative effects of shale oil and gas wells. This contrast may be due to the scale of treatment (i.e., there are more than twice as many shale oil and gas wells as wind turbines constructed

Figure 5: Effects of Shale Well Arrival Inside and Outside Important Bird Areas (Disaggregated by Characteristic)



Notes: Figure reports coefficient estimates with 90% and 95% confidence intervals from difference-in-differences specifications analogous to those reported in Figure 4, estimated separately for CBC circles inside and outside important bird areas.

during the 2000-2020 period) and intensity of treatment (i.e., shale oil gas wells generate constant noise and light pollution, water disturbances, and road traffic).

Shale oil and gas production and wind energy generation each present important environmental and energy trade-offs. Natural gas production from shale formations may ease the transition from dirtier fossil fuels like coal and deliver local economic stimulus, but may also delay the transition to renewable energy sources (Gürsan and de Gooyert, 2021). Wind energy represents a key component of the clean energy transition, but can also impose localized harm or disturbances on wildlife. Mitigation strategies to minimize adverse effects of both energy infrastructure types are feasible (May et al., 2015; McClung and Moran, 2018), and should be implemented broadly, with particular emphasis on reducing negative wildlife impacts inside sensitive habitats. For instance, Ellis et al. (2022) and May et al. (2021) demonstrate how to model wind infrastructure siting to maximize energy generation while minimizing habitat disruptions for birds. Thompson et al. (2015) suggest clustering shale oil and gas wells onto multi-well pads to reduce sprawl and locating wells along existing roads rather than building new ones.

This study goes beyond model-based approaches or site-specific case studies – which document heterogeneous and localized effects of shale wells and wind turbines on wildlife – to offer population-level estimates. Results dispel major concerns over adverse effects of wind energy generation on birds at the population level – though impacts on particularly sensitive species and habitats should not be disregarded. In contrast, results highlight significant negative effects of fracking on bird populations and biodiversity, particularly in sensitive bird habitats. Given that birds generate substantial economic benefits for rural communities and provide essential ecosystem services, these findings highlight additional environmental costs of shale oil and gas production that should be accounted for when formulating energy land-use policy.

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Appendix

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

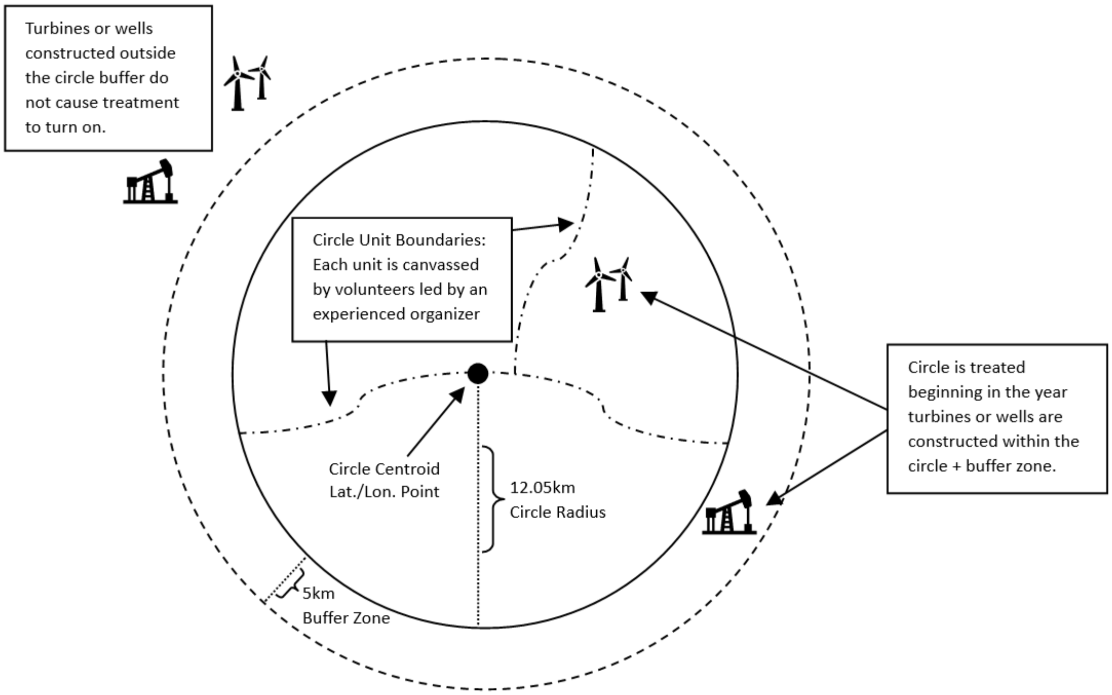
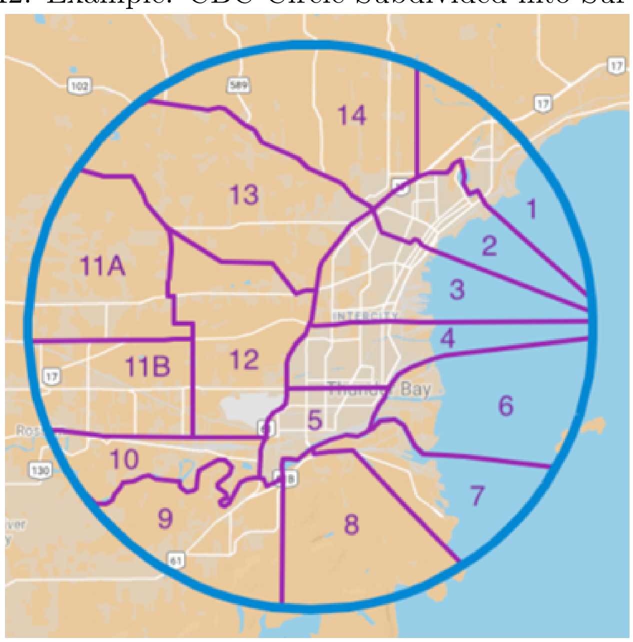
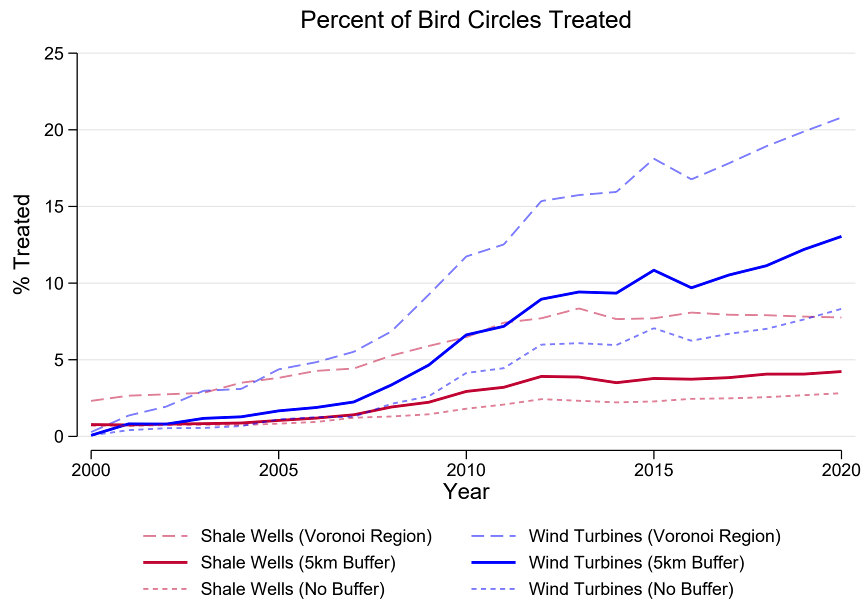


Figure A2: Example: CBC Circle Subdivided into Survey Units



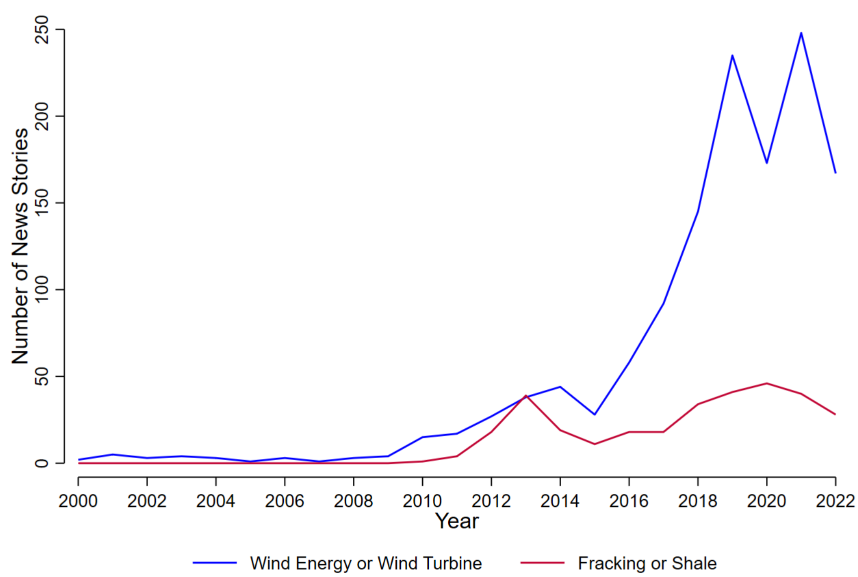
Source: Thunder Bay Field Naturalists (2021)

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



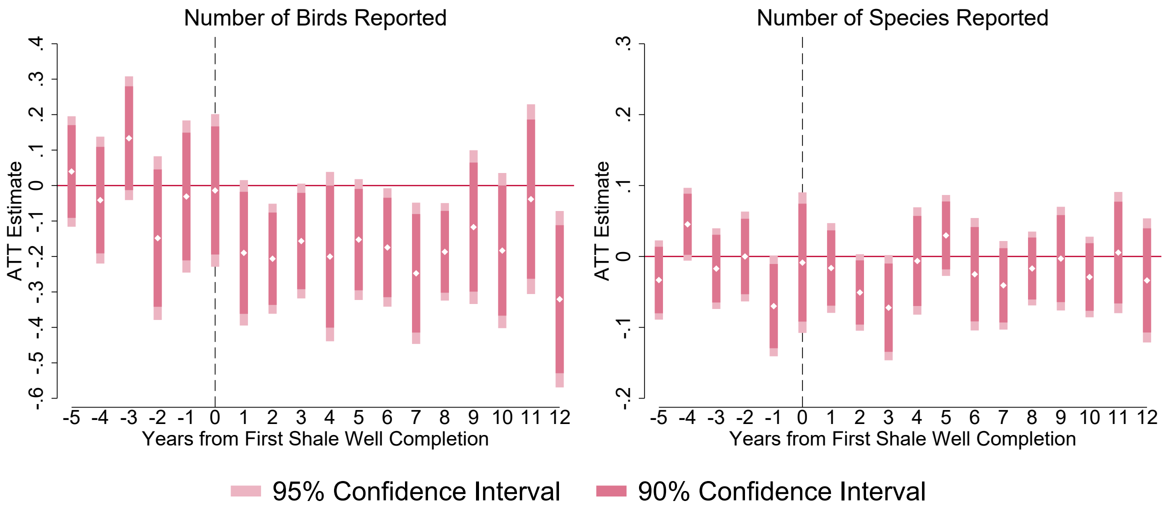
Note: Percentage of CBC Circles with shale well or wind turbine presence (2000-2020), under alternative treatment definitions.

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



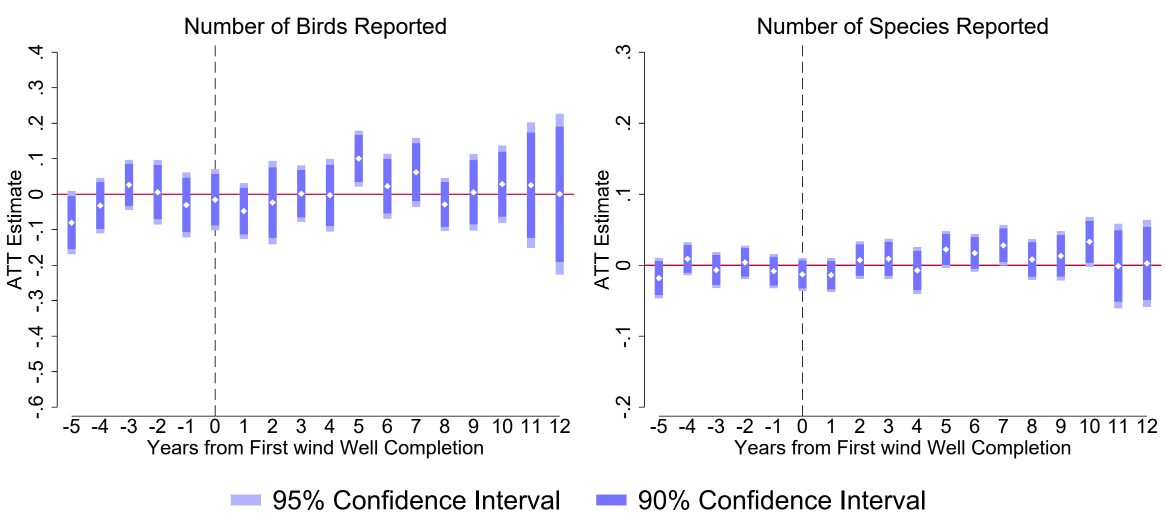
Note: Number of US news stories covering effects of wind or shale on birds, from the International Newsstream Database. Keyword searches were conducted for (i) "Birds" AND ("Fracking" OR "Shale") and (ii) "Birds" AND ("Wind Energy" OR "Turbines"). News stories were restricted to the United States between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

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 Callaway and Sant'Anna (2021)'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 Callaway and Sant'Anna (2021)'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.

Table A1: 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 Callaway and Sant'Anna (2021)'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 A2: 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 A1.

Table A3: 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

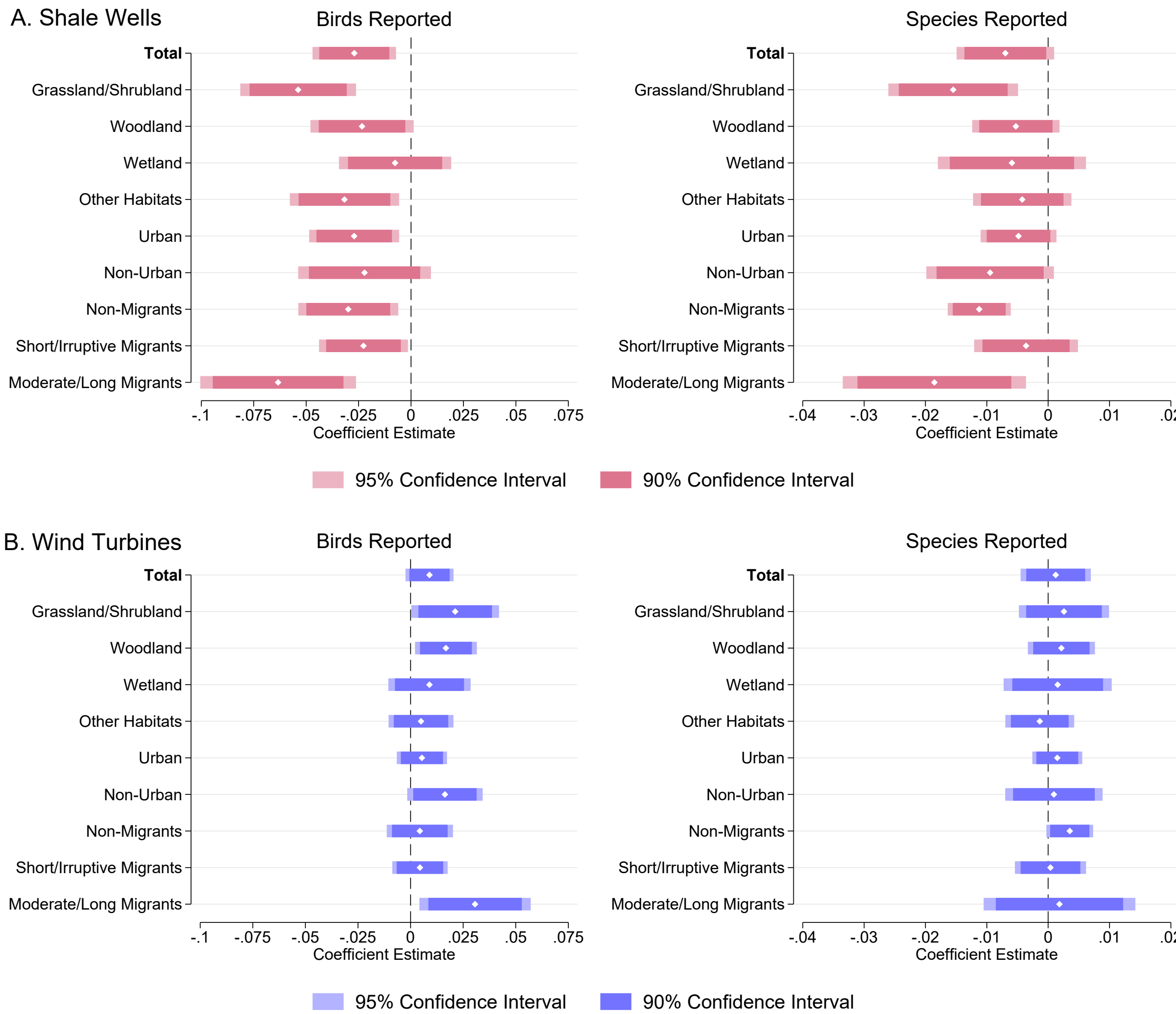
Note: Upper panel of the table reports coefficient estimates, standard errors, and p-values from difference-in-differences specifications that regress number of birds counted (total and disaggregated by characteristic) on relative period indicators before and after the year wind turbines were first constructed within 5km of the border of a CBC circle (control group = never-treated circles) using Callaway and Sant'Anna (2021)'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 A4: 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

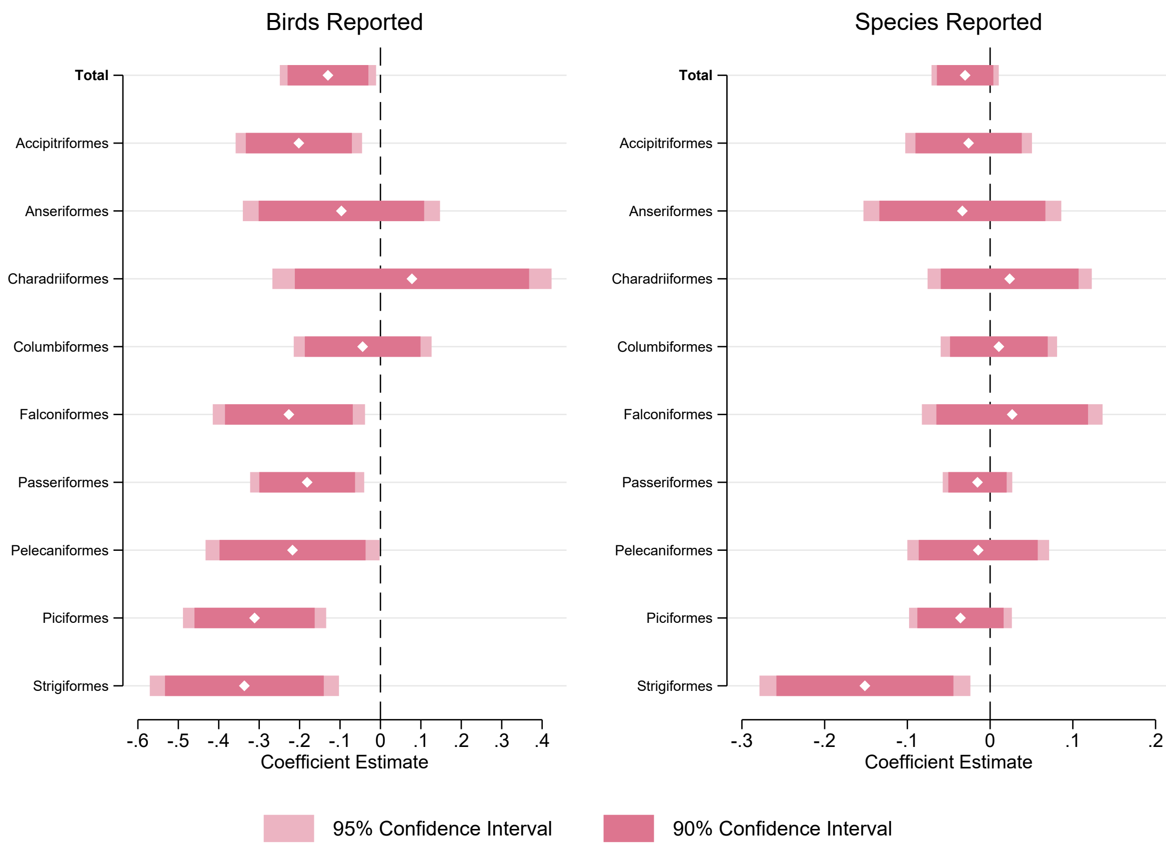
Note: Refer to note under Table A3.

Figure A7: Poisson Model with Untransformed Counts



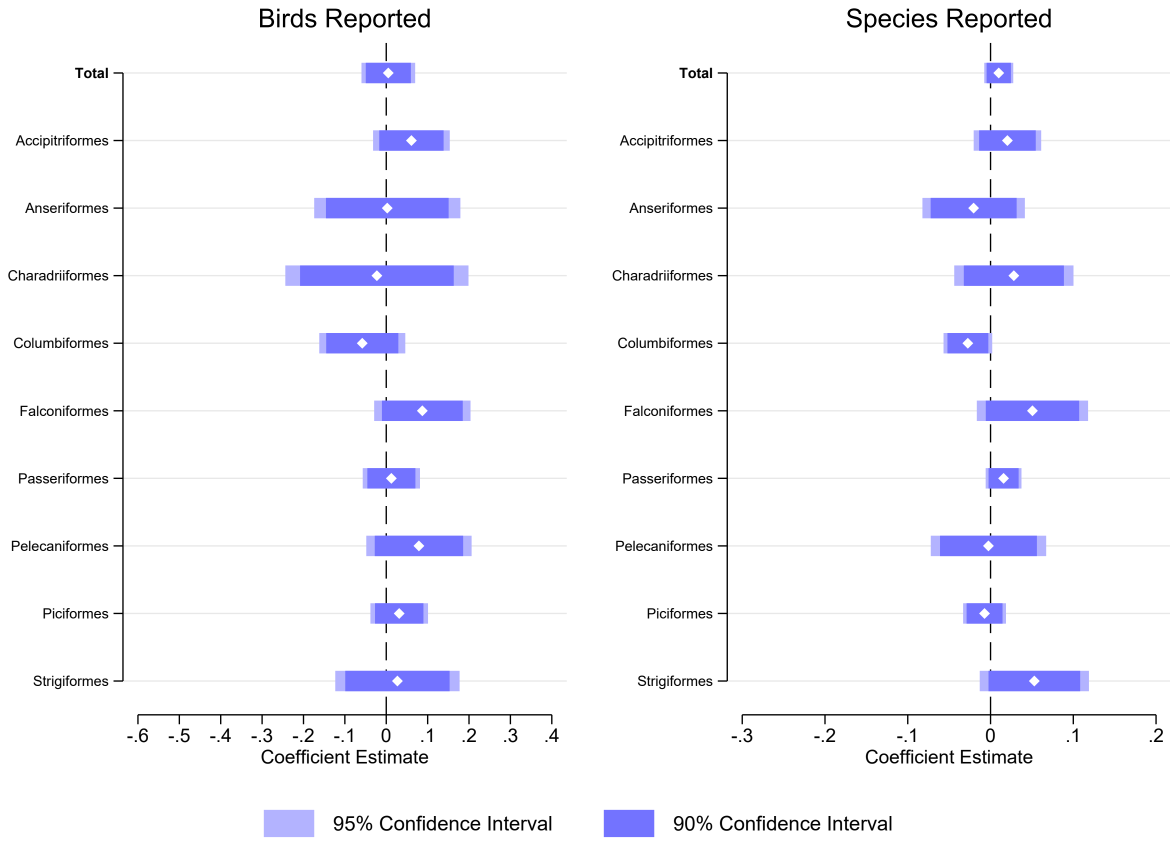
Figures report coefficient estimates with 90% and 95% confidence intervals from estimation of a Poisson model of birds or species counted (total and disaggregated by bird characteristic), using a continuous treatment definition (i.e., the inverse hyperbolic sine of the cumulative number of shale wells 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.

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

Figure A10: Poisson Model with Random Effects and Grid-Square Clustered Errors

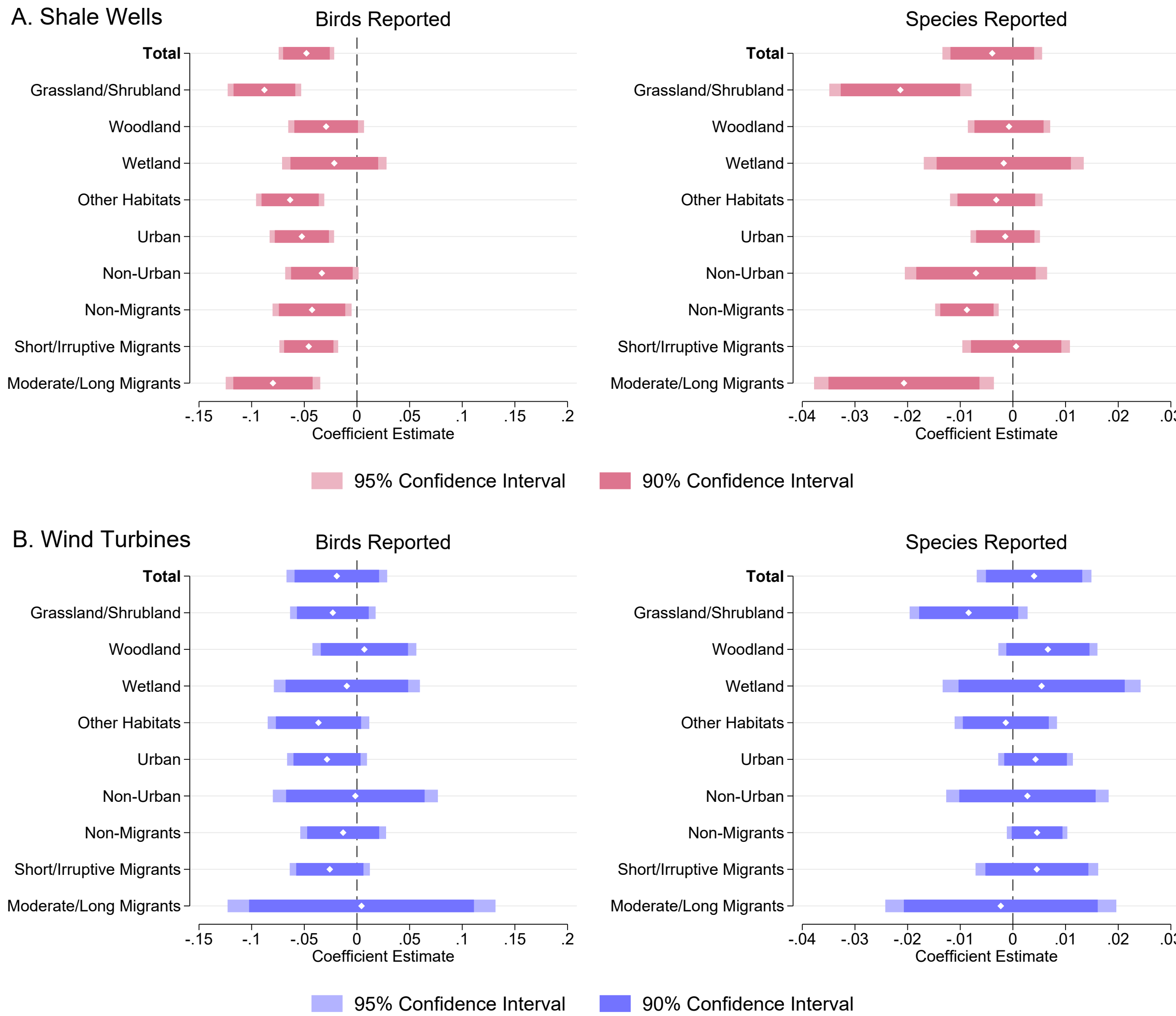


Figure reports results from specification analogous to Figure 4 – including year fixed effects and all the standard covariates – but with random circle effects and standard errors clustered at a 50km-by-50km grid square level to account for localized spatial correlation in outcomes.

Figure A11: Correlated Spatial Random Effects Model

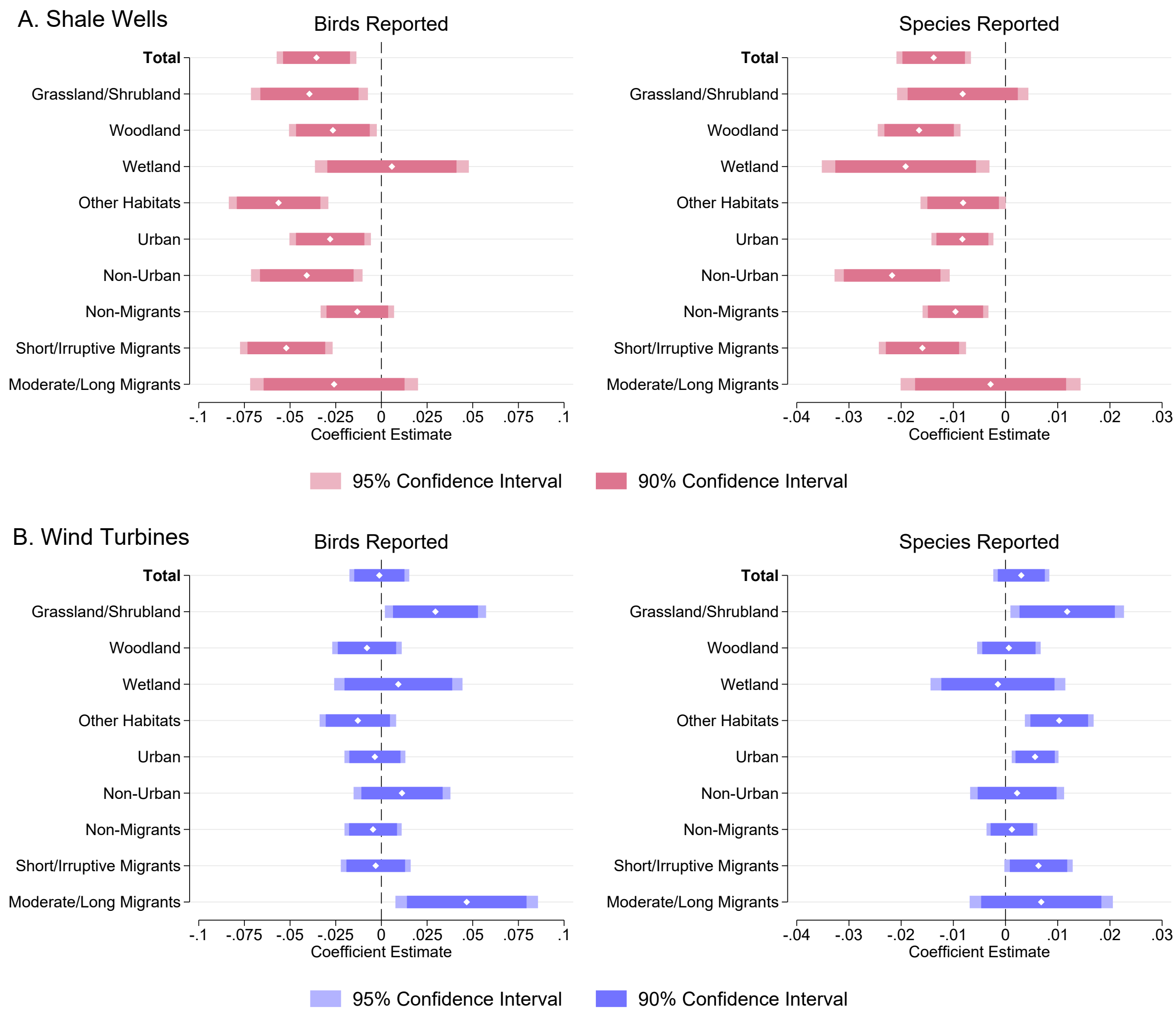


Figure reports results analogous to those described in Figure 4 – including year fixed effects and all the standard covariates – but using a correlated spatial random effects model based on a non-truncated inverse-distance weight matrix between CBC centroid points. The model includes spatial lags for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

Figure A12: Difference-in-Differences (OLS) with State-Year Fixed Effects

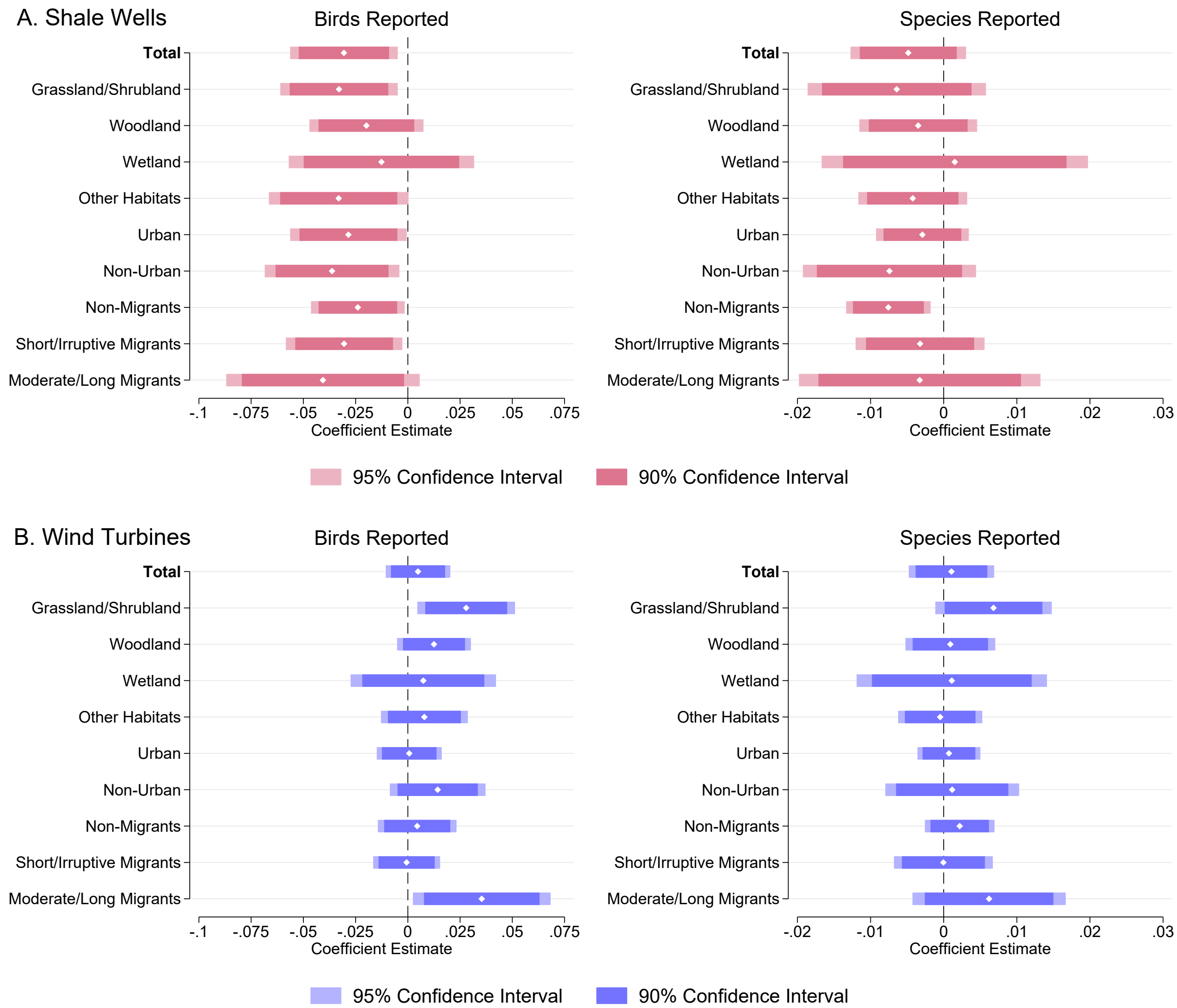
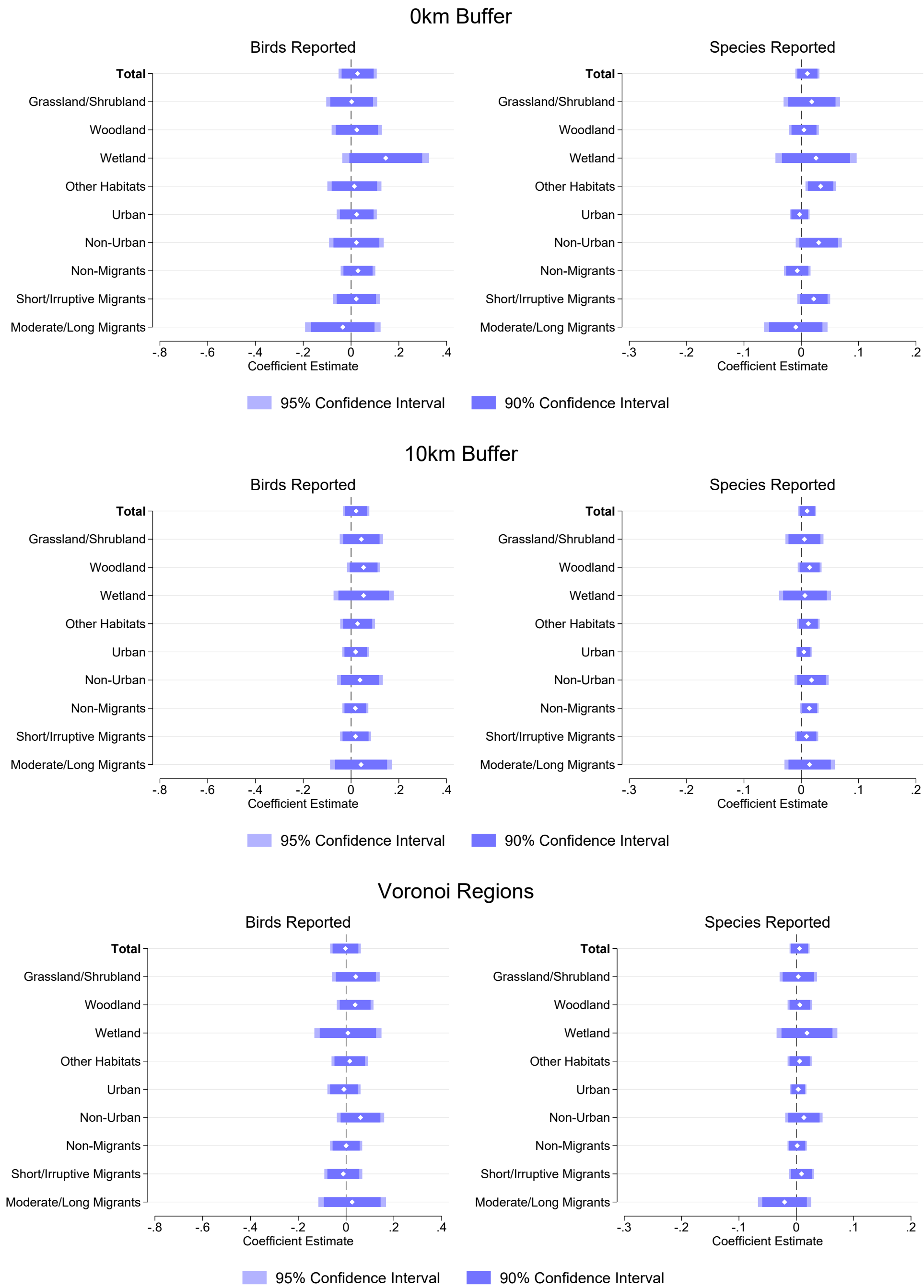


Figure reports results analogous to those in Figure 4, using the difference-in-differences specification defined in Equation 1, an OLS estimator, and continuous treatment definitions defined as the inverse hyperbolic sine of the cumulative number of shale wells or wind turbines operating within 5km of 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.

Figure A13: Shale Well Treatment: Robustness to Alternative Buffer Zones

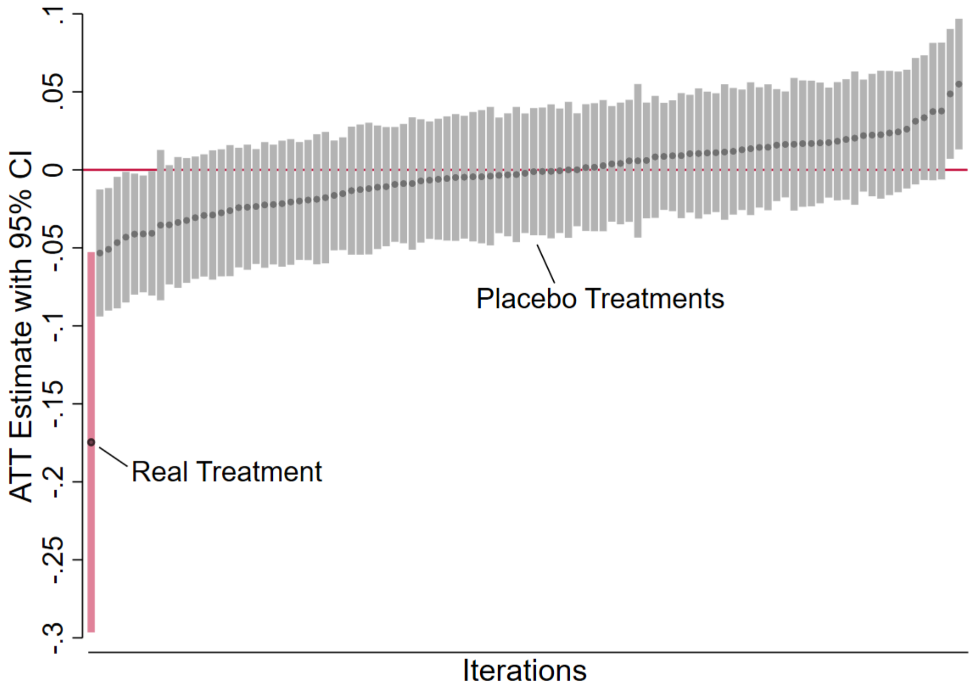
Note: Figures are organized analogously to Figure 4. Top sub-figures use an alternative treatment definition wherein circles are treated in and after the year shale wells are first drilled within the strict boundaries of a CBC circle. This definition assumes no spillover effects from nearby shale wells. 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 A14: Wind Turbine Treatment: Robustness to Alternative Buffer Zones



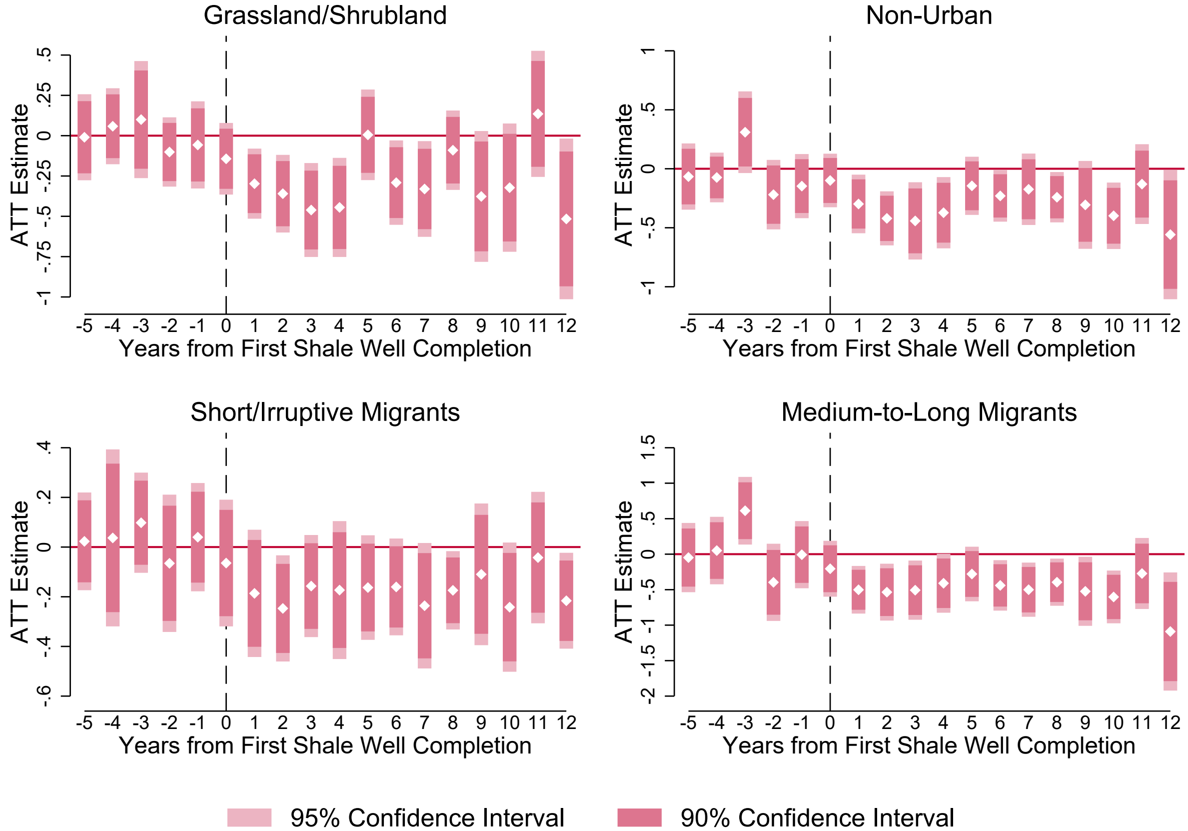
Note: Figures are organized analogously to Figure 4. Top sub-figures use an alternative treatment definition wherein circles are treated in and after the year wind turbines are first constructed within the strict boundaries of a CBC circle. This definition assumes no spillover effects from nearby shale 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.

Figure A15: 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.

Figure A16: Shale Well Arrival: Event Studies for Selected Characteristics



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

Table A5: 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

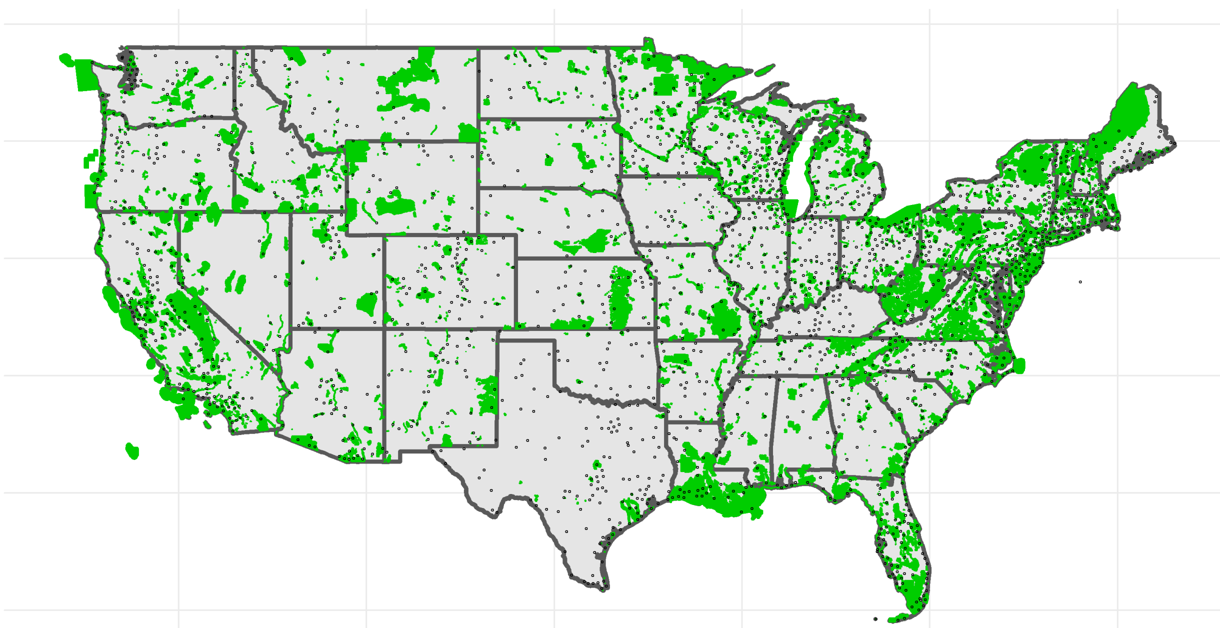
Source: National Audubon Society (2022)

Table A6: 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

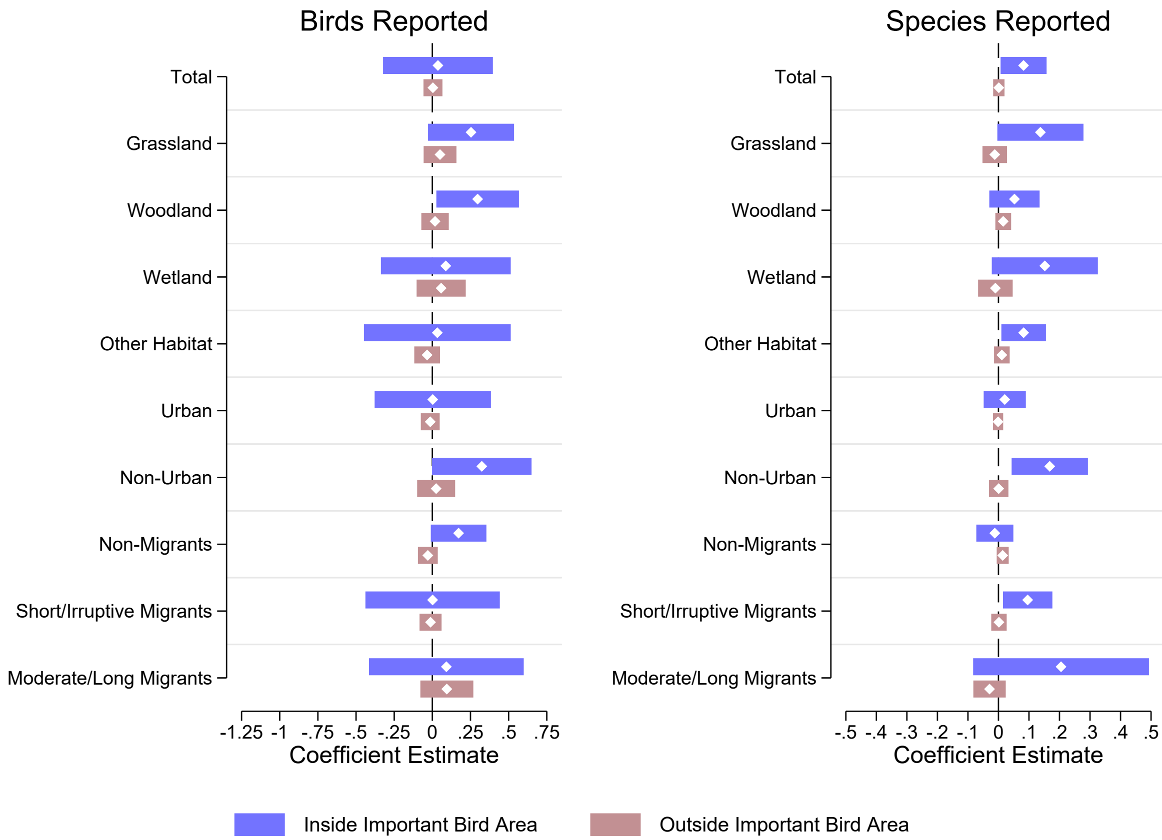
Note: Upper two panels report coefficient estimates, standard errors, and p-values, as well as sample sizes and baseline dependent variable means, for regression of human population in CBC circle's county on relative time indicators around the year of shale well or wind turbine arrival, using Callaway and Sant'Anna (2021)'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.

Figure A17: CBC Circle Locations Relative to Important Bird Areas (in Green)



Source: National Audubon Society (2023).

Figure A18: 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.