Quantifying the Effects of Fracking and Wind Turbines 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 during this period to estimate the effects of these energy land-use changes on bird populations and biodiversity, which are key bellwethers of ecosystem health. Results show that the onset of shale oil and gas production reduces subsequent bird population counts by 16% – or 4.25 birds per well drilled – even after adjusting for location and year fixed effects, weather, and counting effort. Wind turbines do not have any measurable impact on bird counts. Negative effects of shale are not driven by changes in human population, and are larger when wells are drilled within important bird habitats.

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

JEL Codes: Q20, Q35, Q42, Q57

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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 (Energy Information Administration, 2022).[1] 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 quantifying their effects on wildlife at the population level has proven difficult (May et al., 2017).

Shale oil and gas production enabled by hydraulic fracturing, or "fracking," techniques creates significant ecosystem disturbances at both drilling and production stages (Jackson et al., 2014). 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.

Wind energy installations introduce tall, dispersed structures with rotating turbines and transmission lines that may impact wildlife, particularly birds and bats,[2] through a variety

[1] 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 (Energy Information Administration, 2023). The number of shale wells grew from 3,088 in 2000 to 242,641 in 2020 (Rystad Energy, 2022). Future shale oil and gas trends depend on the evolution of global energy prices and climate policy. 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). Land-use for wind must grow by a further 4-7 times by 2050 to meet decarbonization targets (Net-Zero America, 2023).

[2] Bats may be more impacted than birds by wind turbines (Schuster et al., 2015; Hayes, 2013). I focus on

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).

Most estimates of the impacts of fracking and wind energy installations on birds are based on single- or multi-site case studies (e.g., Barton et al., 2016), which are then extrapolated. 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. The study by Miao et al. (2019) makes a methodological advance by estimating wind energy effects on birds at the population level and by accounting for potential omitted variable bias using fixed effects models.

This paper builds on the population-level approach 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

birds in this study due to data availability and birds' relevance as indicators of ecosystem health (Fraixedas et al., 2020).

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 estimate difference-in-differences specifications around the year of arrival of shale wells or wind turbines within the vicinity of a CBC count location ("circle") to estimate the effects of each of these energy land-use changes on bird populations and species diversity. I control for circle and year fixed effects, as well as weather and counting effort to minimize omitted variable bias, and implement Callaway and Sant'Anna (2021)'s *csdid* estimator to avoid bias introduced by staggered treatment timing and heterogeneous treatment effects.

Debate over energy land-use impacts on birds has been dominated by discussion of wind turbines, with 173 stories in major 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 A1). Despite the focus on wind turbines in public discourse, I find no measurable effect of wind energy installations on bird population counts or species diversity. In contrast, I find that shale oil and gas production exerts significant negative effects on bird population counts, as well as significant negative effects on bird species diversity when wells are drilled inside important bird habitats.

This study advances research on population-level wildlife impacts of energy land-uses along several dimensions. First, I estimate comparable effects for two distinct energy land-use changes using a common data structure and methodology. Second, I estimate effects for the entire lower-48 United States over a twenty-year window 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 bias introduced by inclusion of already-treated units in standard fixed effects models (Goodman-Bacon, 2021).

2 Birds: Economic and Environmental Impacts

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 migratory bird hunting activities, resulting in US$2.3 billion in expenditures across 15 million individual hunting trips. Both birdwatchers and hunters tend to have higher-than-average spending power, increasing their contributions to rural economic activity (U.S. Fish and Wildlife Service, 2016b).

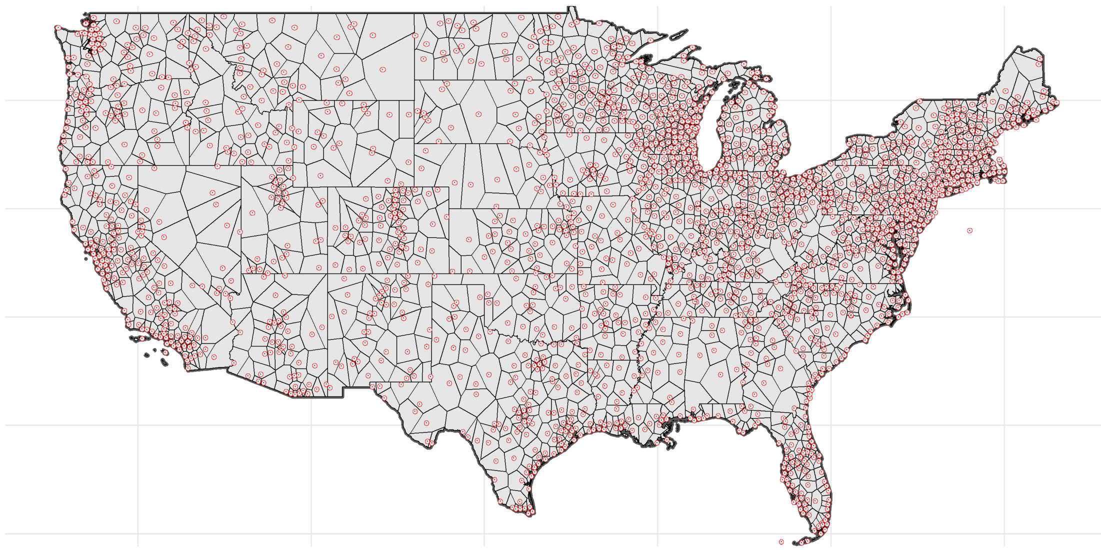
Birds are also indicators of broader environmental health and provide extensive ecosystem services (Fraixedas et al., 2020). These include pest and disease control (Frank and Sudarshan, 2023; Markandya et al., 2008), pollination, seed dispersion, and regulation of forest and wetland health (Gaston, 2022; Whelan et al., 2008). 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). Birds' economic and environmental contributions should be taken into account when evaluating costs and benefits of energy land-use changes.

3 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 around a geolocated central point. 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. Volunteers' routes are carefully coordinated to maximize coverage within the circle while minimizing double-counting. Critically, CBC methodology and (in almost all cases) circle locations were unchanged over the study period.[3]

[3]The Christmas Bird Count presents several major advantages over alternative 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; (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). Nevertheless, the CBC has several limitations: (i) it reports counts from a single day in December, which, in many parts of the country, means it misses breeding birds and significant shares of total birds that are not present in the winter; (ii) the CBC offers dense coverage of territory in the US Northeast, Midwest, Gulf Coast, and West Coast, but sparser coverage in the West and non-coastal South.

Figure 1: Christmas Bird Count Locations within Voronoi Tessellations



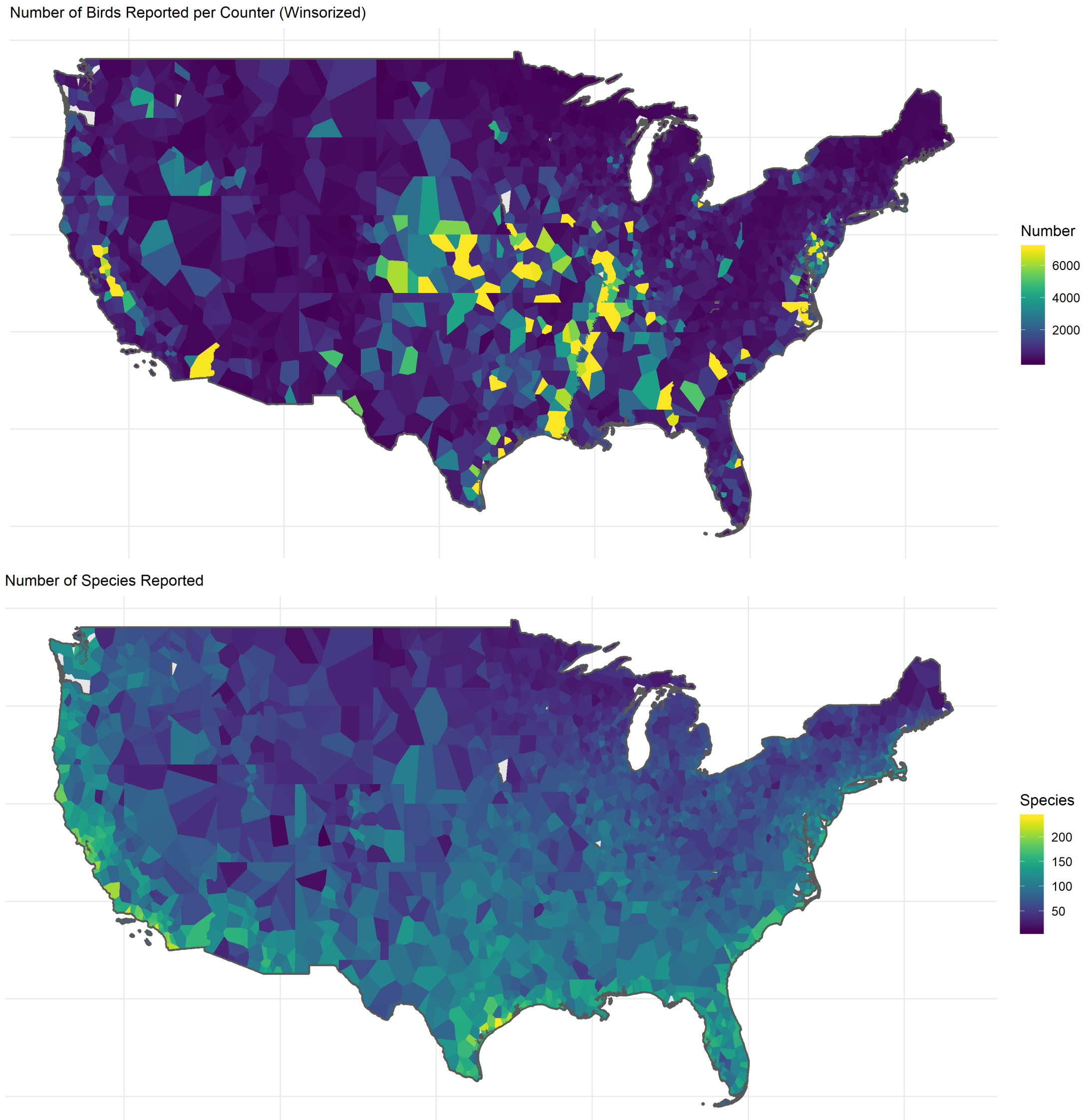
Source: National Audubon Society (2022)

Figure 1 presents a map of CBC circles for the lower-48 United States, as well as Voronoi tesselations corresponding to each circle.[4] 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 Coast, and in the Central South. Species diversity is highest along the coasts.

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.

[4]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.

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

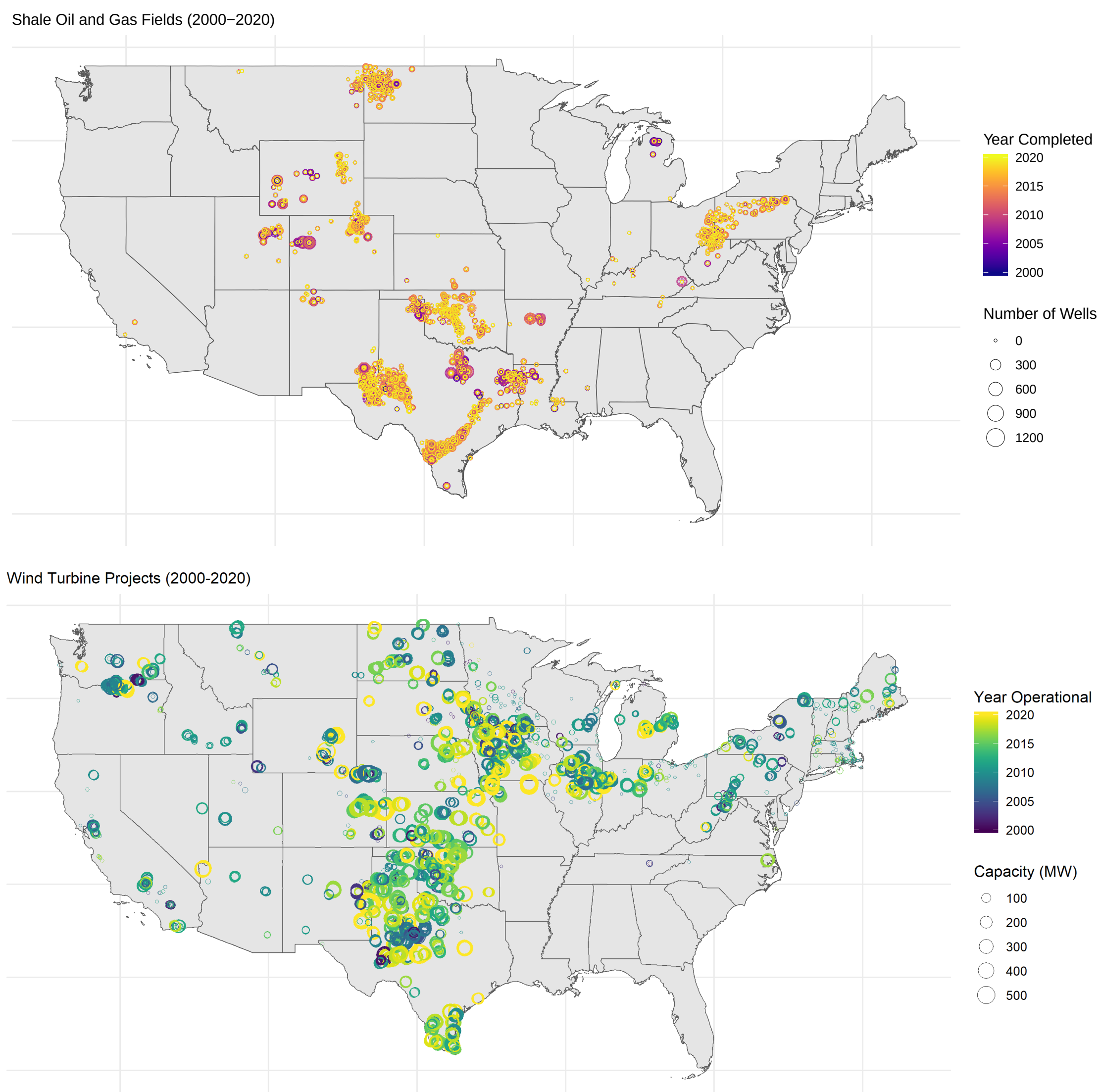


Source: National Audubon Society (2022)

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, as well as project characteristics such as turbine height, megawatt capacity, and rotor swept area, 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).

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



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

4 Methodology

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 identify if and when wells or turbines are constructed within proximity of a circle (i.e., within 17.05km or the circle centroid, or 5km of the circle boundary).[5] 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} may measure 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*).[6]

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 (and continuing in subsequent periods) when (i) wells were completed, or (ii) turbines were constructed in proximity to circle c, and assumes a value of 0 otherwise.[7] 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) and counting effort (number of counters participating), as well as circle and year

[5] 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 (i.e., circles are only treated if a well or turbine is built within the boundary of the circle, and (ii) larger Voronoi regions around each circle. Appendix Figure A2 plots the percentage of CBC circles treated over time using these alternative definitions.

[6] I winsorize population counts at the 99th percentile to account for plausibly spurious outliers, wherein large round numbers of particular species (e.g., 2 million red-winged blackbirds) are reported.

[7] There is a trade-off between this binary pre/post treatment indicator, which allows implementation of Callaway and Sant'Anna (2021)'s more credible *csdid* estimator, and continuous treatment measures (e.g., number of wells or turbines), which yield marginal treatment effect estimates but are not compatible with modern estimators. In Appendix Figures A3-A4, I present results from re-estimating Equation 1 using OLS and continuous versions of T_{ct}, defined as the inverse hyperbolic sine of the number of shale wells or turbines operating in proximity to a CBC circle. I discuss results from both estimators in the Results section.

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). Finally, 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.

Causal inference 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 that rely on self-reported bird data. Second, inclusion of circle and year fixed effects and weather and effort covariates substantially reduces omitted variable bias. 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 an event study approach and find they are statistically insignificant.

5 Results

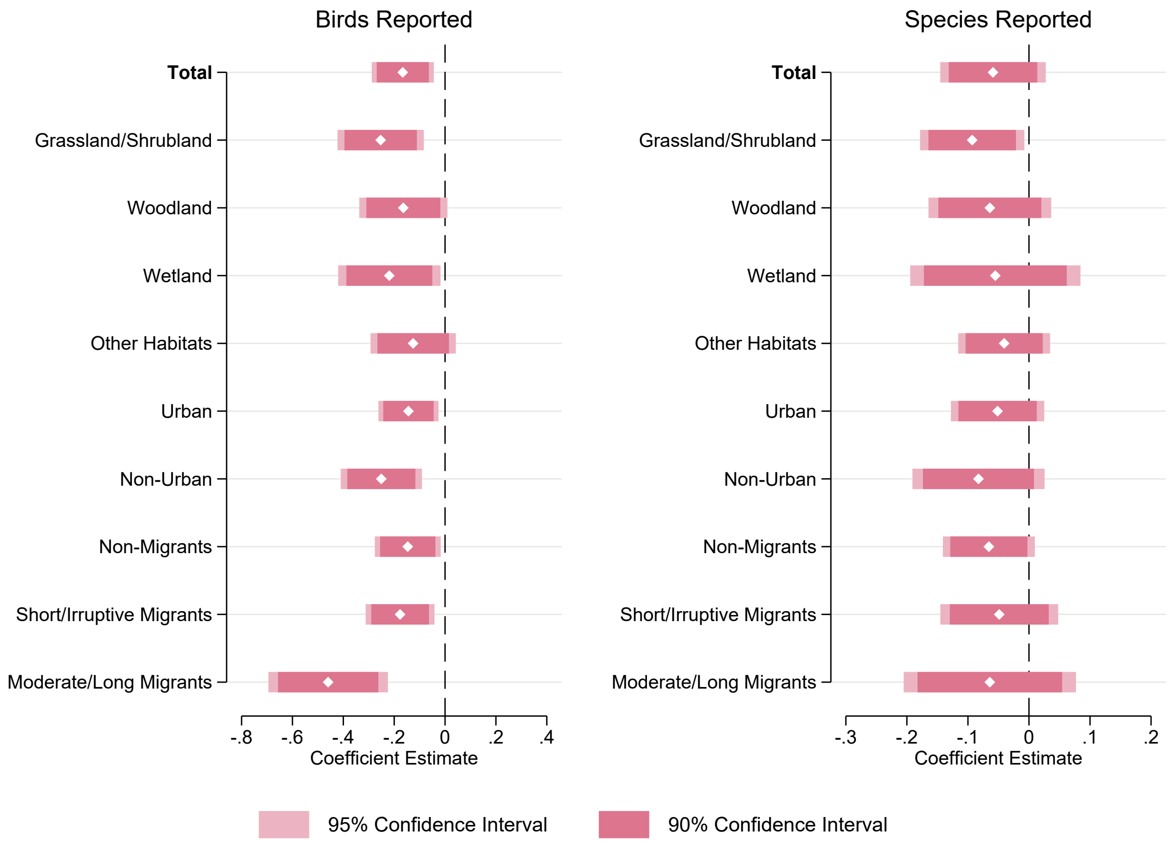
I first report results for shale oil and gas wells, and then wind energy installations. I estimate Equation 1 for total number of birds and species counted, and then separately for birds of characteristics defined as in Soykan et al. (2016): grassland/shrubland, woodland, wetland, and other habitats; urban and non-urban, and non-migrants, short/irruptive migrants, and moderate/long migrants. Figure 4 reports estimates of coefficient β_1 with 90% and 95% confidence intervals for shale wells. Corresponding tables of results and sample statistics are reported in Appendix Tables A1-A2.[8]

Arrival of shale oil and gas wells within 5km of a CBC circle reduces the total number of birds counted in subsequent years by 16% (p = 0.005).[9] 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 in proximity to a CBC circle does not have a statistically significant effect on total species counts, but reduces grassland and shrubland species diversity by 6% (p = 0.032) and weakly reduces species diversity among non-migrants by 4% (p = 0.095). Across all characteristics, point estimates of shale effects on population and species counts are negative.

[8] In Appendix Figures A7-A8, I re-estimate Equation 1 using alternative treatment definitions (0km. buffer and Voronoi regions) as a robustness check. Results using the 0km. buffer lose some precision due to fewer treated units, but point estimates and patterns are consistent. Results using Voronoi regions remain unchanged for wind, and become more significantly negative for shale.

[9] 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 upon switching from control to treated (i.e., 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: $100 \times (e^{(-0.175)} - 1) = -16\%$ (Bellemare and Wichman, 2019).

Figure 4: Effects of Shale Well Arrival on Bird and Species Counts
(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 characteristic) 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. Continuous outcomes are transformed using the inverse hyperbolic since function.

Results for the continuous treatment definition (i.e., number of shale wells operating in proximity to a CBC circle) are similar (see Appendix Figure A3): a 1% increase in number of wells reduces the total bird population count by 0.03% (p = 0.013), which equates to a reduction of 4.25 birds per well drilled.[10] A 1% increase in wells reduces the number of medium-to-long migrant birds by 0.05% (p = 0.059), grassland birds by 0.04% (p = 0.002),

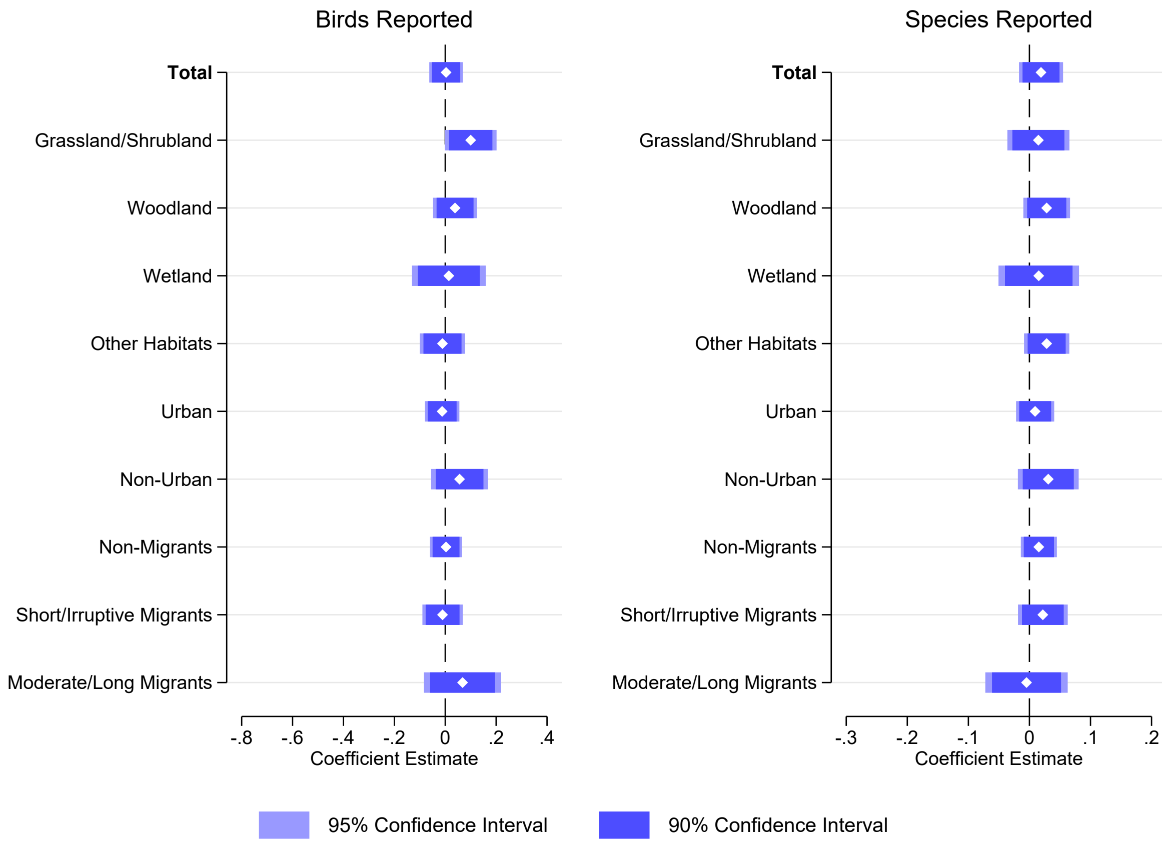
[10]This calculation is based on a baseline (year 2000) average total bird count of 8,253 and an average of 59 shale wells per treated circle.

and non-urban birds by 0.04% ($p = 0.019$). Turning to species diversity, a 1% increase in wells reduces the number of non-migrant species (-0.01%, $p < 0.001$) and grassland species (-0.01%, $p = 0.080$). 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 A9. 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.

Results for wind energy installations are reported in Figure 5 (corresponding to Appendix tables A3-A4). Arrival of wind turbines within 5km. of a CBC circle has no measurable effect on total bird population or species counts, nor does it have a measurable effect when results are disaggregated by characteristic or taxonomic order (Appendix Figure A10). Null effect estimates are quite precise: the 95% confidence interval for turbine effects on total population counts ranges from -0.063 to 0.071; the confidence interval for total species counts ranges from -0.008 to 0.028. 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, with the exception of a significant *positive* effect on number of grassland birds (Appendix Figure A4).

Figure 5: Effects of Wind Turbine Arrival on Bird and Species Counts (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 time indicators around the year 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 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. Continuous outcomes are transformed using the inverse hyperbolic since function.

5.1 Mechanisms

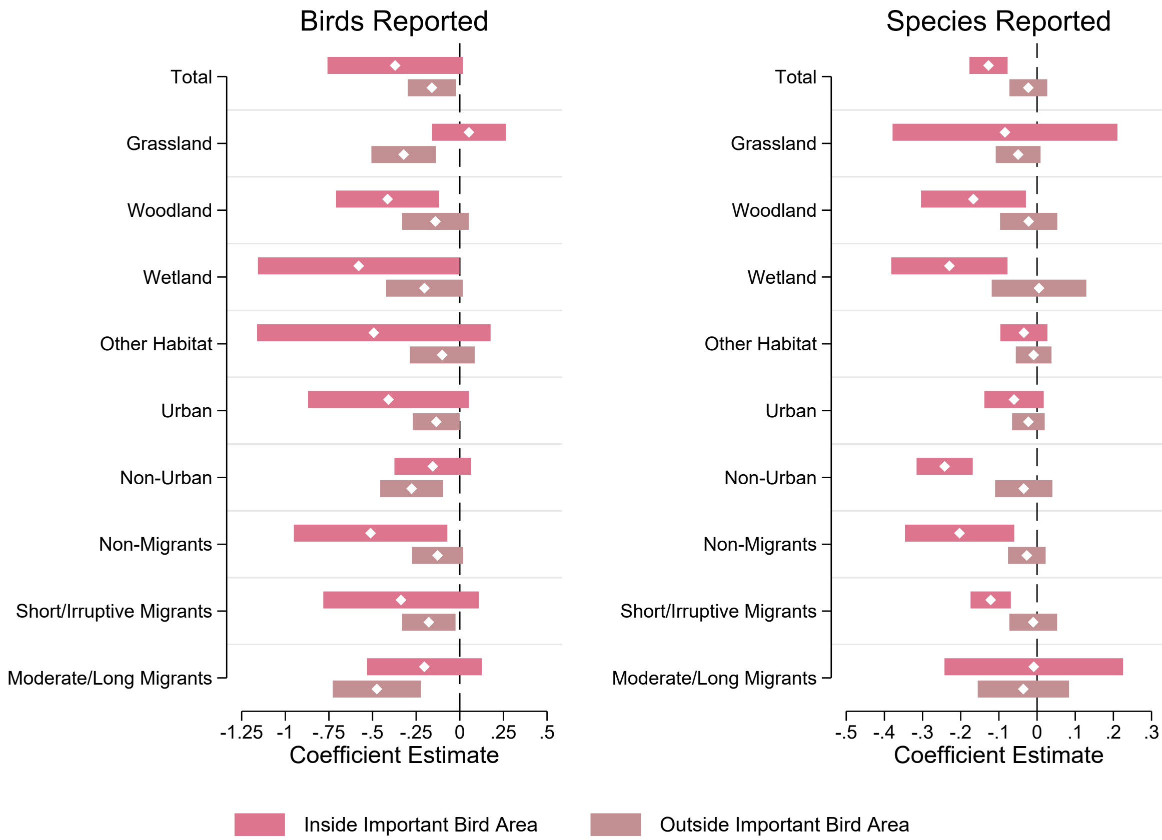
What factors underlie the significant negative effects of shale wells on birds? I first test for the possibility that shale oil and gas production or wind energy installations attract human in-migration, which could in turn exert negative effects on birds independently of direct energy land-use impacts. 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 approach to assess whether increased human activity affects bird counts.[11] 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 significant effects 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 production and transportation processes.

Finally, I explore heterogeneity in effects inside and outside of 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 Audobon Society (National Audubon Society, 2023), and mapped in Appendix Figure A11. Results, presented in Figure 6, suggest that 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.[12]

[11]This approach (see more detailed description in Appendix A6) avoids biases inherent in traditional sensitivity analysis, wherein a hypothesized mediator (e.g., human population) is alternatively included or omitted from a regression model to assess whether this changes the treatment effect estimate. Sensitivity analysis introduces bias in the presence of confounders (Acharya et al., 2016).

[12]Analogous results for wind turbine arrival are presented in Appendix Figure A12. Estimation of zero effects of turbine arrival on bird population does not change when focusing inside or outside important bird areas. Effects on species diversity are zero outside important bird areas, and zero or positive within important bird areas. This somewhat surprising finding reinforces the conclusion that turbines do not have measurable negative impacts on birds at the population level.

Figure 6: 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 that regress number of birds or species counted (total and disaggregated by bird characteristic) on relative time indicators around the year shale wells were first drilled 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 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. Continuous outcomes are transformed using the inverse hyperbolic since function.

6 Conclusion and Policy Implications

This study estimates comparable population-level effects of major energy land-use changes (i.e., shale oil and gas production and wind energy generation) on bird populations and species diversity for the lower-48 United States between 2000 and 2020, using data from the National Audubon Society's Christmas Bird Count. The methodology controls for weather and effort covariates as well as circle and year fixed effects, and implements Callaway and Sant'Anna (2021)'s *csdid* estimator to avoid biases afflicting standard two-way fixed effects estimators. Results show that arrival of shale oil and gas production reduces subsequent bird population counts by 16% (or by 0.03% for each 1% increase in the number of wells, amounting to 4.25 birds per well drilled), and also reduces species diversity when wells are drilled inside important bird areas. Negative effects of shale are largest for migratory birds, non-urban birds, and grassland birds. Focusing instead on taxonomic orders, negative effects of shale oil and gas production are largest for *Strigiformes*, *Piciformes*, and *Falconiformes*. Wind energy installations have no statistically significant effects on bird populations or species diversity.

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 may also impose localized harm on wildlife. Mitigation strategies to minimize adverse effects of both energy land-uses 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.

Summing up, this study goes beyond site-specific case studies – which document heterogeneous and localized effects of shale wells and wind turbines on wildlife – to offer population-level estimates that take avoidance behaviors into account. Results dispel major concerns over adverse effects of wind energy generation on birds. 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 (e.g., recreation value through birdwatching and hunting) and provide essential ecosystem services, these findings highlight additional costs of shale oil and gas production that should be accounted for when formulating energy land-use policy.

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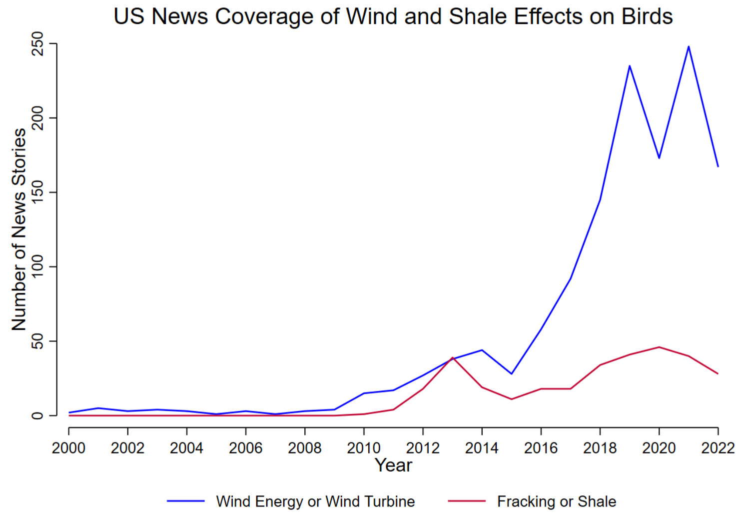
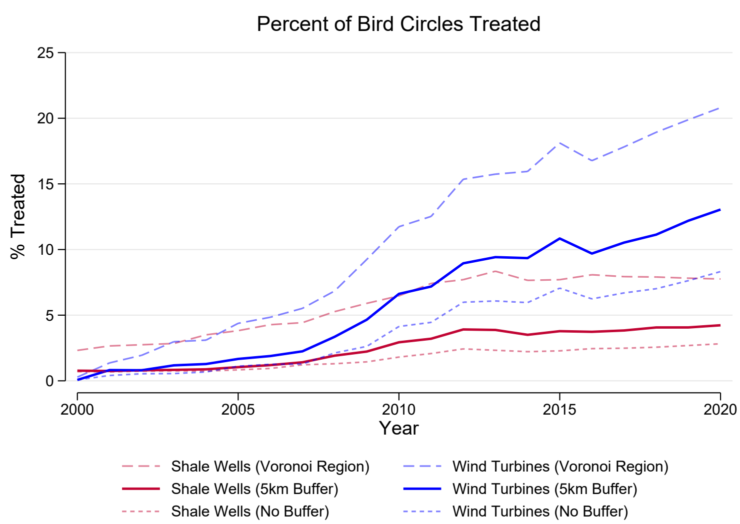
Appendix

Figure A1: Number of US News Stories Covering Effects of Wind or Shale on Birds



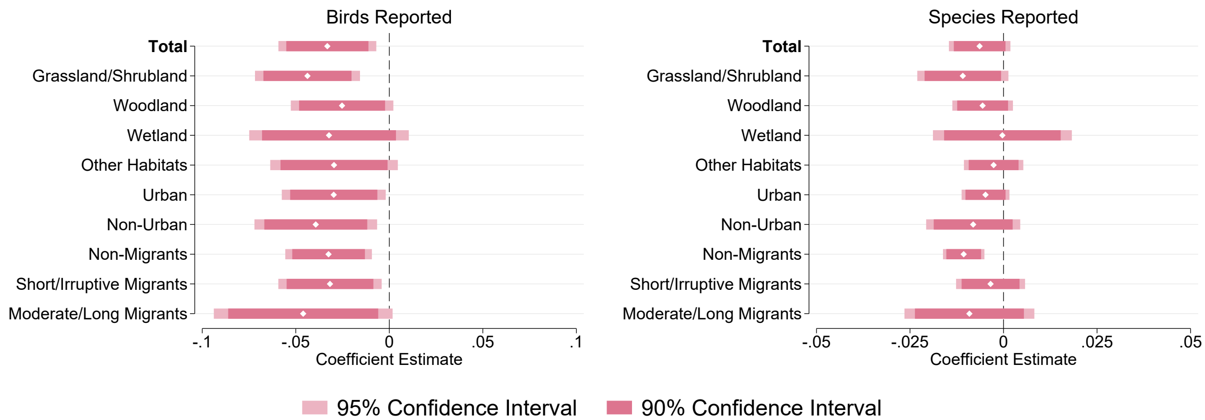
Note: Data on news coverage drawn from the International Newsstream Database. Keyword searches were conducted for (i) "Birds" AND ("Fracking" OR "Shale") and (ii) "Birds" AND ("Wind Energy" OR "Turbines"). News stories were restricted to the United States between January 1st 2000 and December 31st 2022.

Figure A2: CBC Circles with Shale Well or Wind Turbine Presence



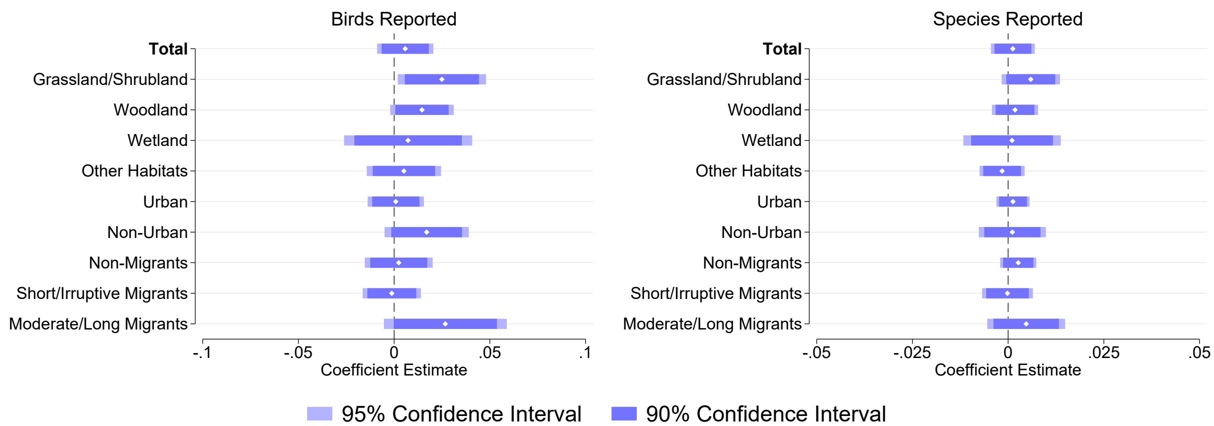
Note: Data on CBC circles are drawn from National Audubon Society (2022). Data on wind turbines are from US Geological Survey (2022). Data on shale wells are from Rystad Energy (2022).

Figure A3: Effects of Continuous Shale Treatment (Number of Wells)



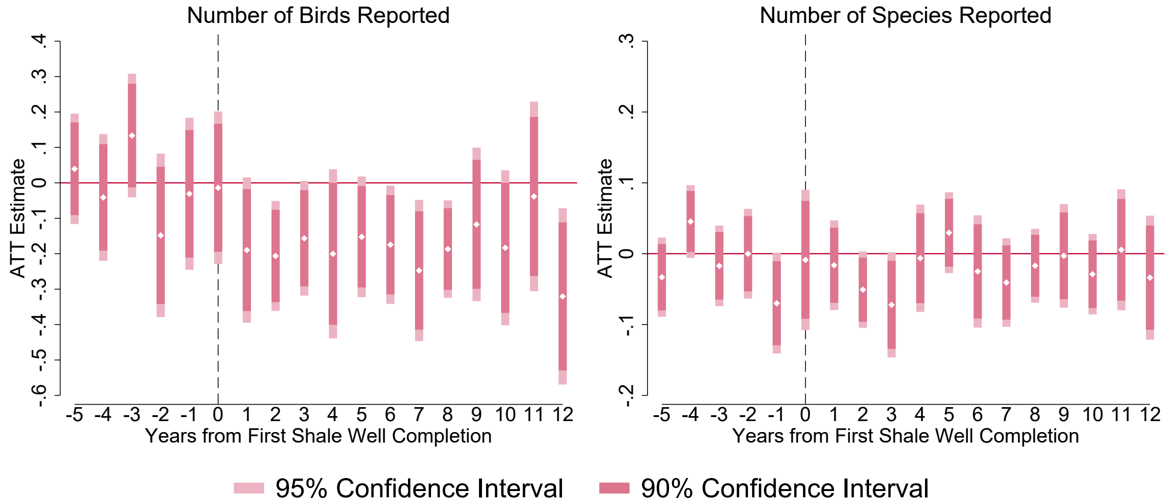
Note: Figure reports coefficient estimates with 90% and 95% confidence intervals from difference-in-differences specifications that regress number of birds or species counted (total and disaggregated by characteristic) on the number of shale wells active within 5km. of the boundary of a CBC circle in a given year. 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 OLS. Continuous treatment and outcomes are transformed using the inverse hyperbolic sine function.

Figure A4: Effects of Continuous Wind Treatment (Number of Turbines)



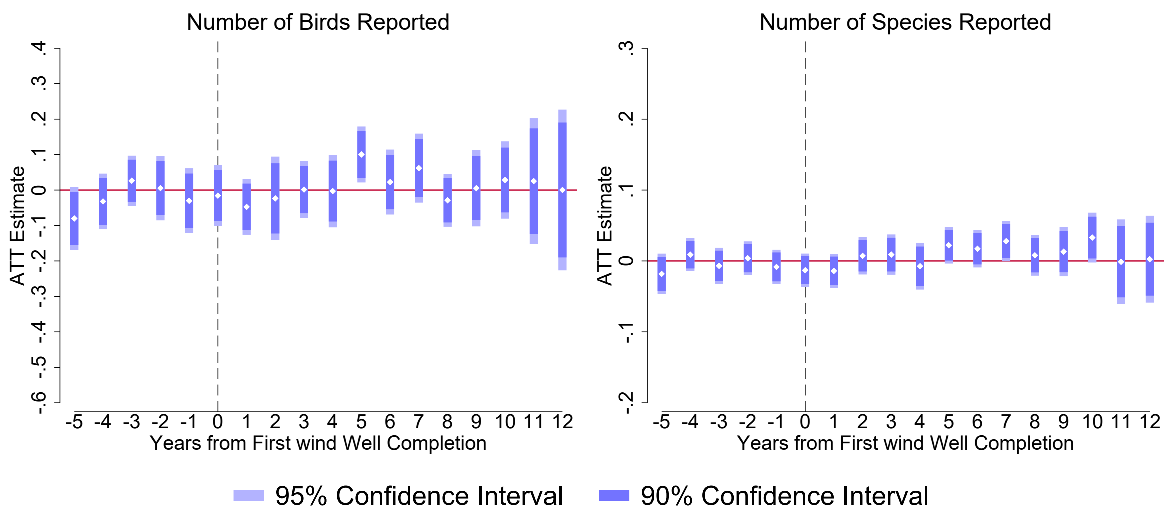
Note: Figure reports coefficient estimates with 90% and 95% confidence intervals from difference-in-differences specifications that regress number of birds or species counted (total and disaggregated by characteristic) on the number of wind turbines active within 5km. of the boundary of a CBC circle in a given year. 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 OLS. Continuous treatment and outcomes are transformed using the inverse hyperbolic sine function.

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 supports 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 supports 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)	-0.175	-0.275	-0.171	-0.222	-0.125	-0.153	-0.264	-0.157	-0.185	-0.464
St. Error	(0.062)	(0.086)	(0.087)	(0.104)	(0.086)	(0.061)	(0.082)	(0.067)	(0.069)	(0.119)
p-val	0.005	0.001	0.049	0.033	0.144	0.012	0.001	0.020	0.008	0.000
Coef. (DID)	-0.033	-0.044	-0.025	-0.032	-0.030	-0.030	-0.039	-0.032	-0.032	-0.046
St. Error	(0.013)	(0.014)	(0.014)	(0.022)	(0.017)	(0.014)	(0.017)	(0.012)	(0.014)	(0.024)
p-val	0.013	0.002	0.071	0.139	0.09	0.036	0.019	0.006	0.025	0.059
n (CS)	27,524	27,337	27,376	27,113	27,521	27,509	27,505	27,504	27,487	26,855
n (DID)	27,924	27,744	27,779	27,537	27,920	27,911	27,906	27,904	27,889	27,284
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 time indicators around 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). Middle panel reports analogous results estimated using OLS and continuous treatment (number of wells). All 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, and cluster standard errors at the circle level. Continuous variables are transformed using the inverse hyperbolic since function. 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	-0.063	-0.033	-0.021	-0.011	-0.023	-0.055	-0.039	-0.02	-0.036
St. Error	(0.023)	(0.029)	(0.035)	(0.057)	(0.021)	(0.019)	(0.035)	(0.023)	(0.029)	(0.054)
p-val	0.178	0.032	0.34	0.72	0.601	0.241	0.118	0.095	0.488	0.502
Coef. (DID)	-0.006	-0.011	-0.006	0.000	-0.003	-0.005	-0.008	-0.011	-0.003	-0.009
St. Error	(0.004)	(0.006)	(0.004)	(0.009)	(0.004)	(0.003)	(0.006)	(0.003)	(0.005)	(0.009)
p-val	0.128	0.080	0.176	0.974	0.513	0.139	0.206	0.000	0.461	0.303
n (CS)	27,524	27,337	27,376	27,113	27,521	27,509	27,505	27,504	27,487	26,855
n (DID)	27,924	27,744	27,779	27,537	27,920	27,911	27,906	27,904	27,889	27,284
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)	0.004	0.065	0.053	0.035	-0.013	-0.007	0.048	0.007	-0.017	0.087
St. Error	(0.034)	(0.052)	(0.044)	(0.075)	(0.045)	(0.035)	(0.059)	(0.032)	(0.041)	(0.080)
p-val	0.897	0.211	0.234	0.636	0.782	0.848	0.411	0.821	0.686	0.276
Coef. (DID)	0.006	0.025	0.015	0.007	0.005	0.001	0.017	0.002	-0.001	0.027
St. Error	(0.007)	(0.012)	(0.008)	(0.017)	(0.010)	(0.007)	(0.011)	(0.009)	(0.008)	(0.016)
p-val	0.440	0.034	0.086	0.669	0.606	0.907	0.130	0.790	0.876	0.102
n (CS)	27,611	27,431	27,465	27,227	27,608	27,598	27,593	27,591	27576	26962
n (DID)	27,924	27,774	27,779	27,537	27,920	27,911	27,906	27,904	27,889	27,284
DV Mean	10,248	912	1,356	3,512	3,919	7,397	2,851	1,420	7,551	1,276

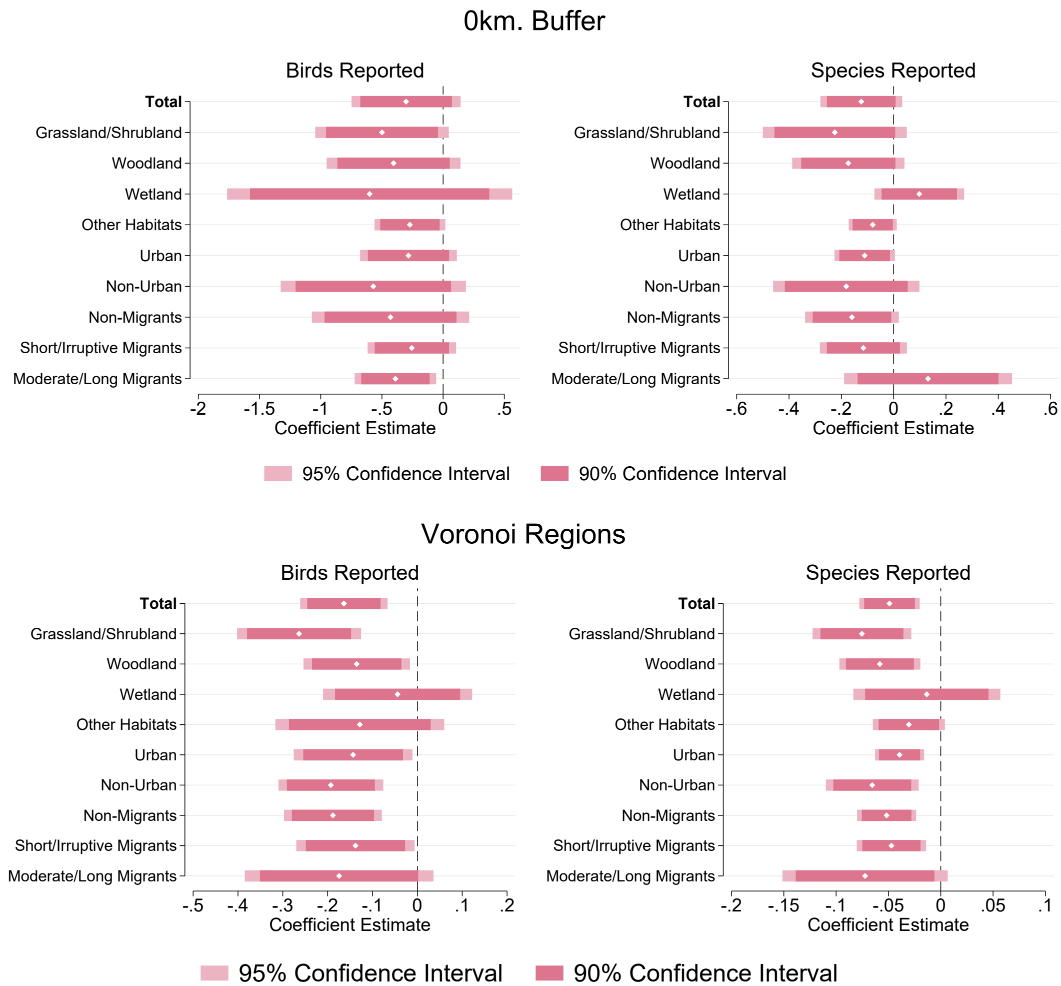
Note: Upper panel of the table reports coefficient estimates, standard errors, and p-values from difference-in-differences specifications that regress number of birds counted (total and disaggregated by characteristic) on relative time indicators around the year wind turbines were first installed within 5km of the border of a CBC circle (control group = never-treated circles) using Callaway and Sant'Anna (2021)'s *csdid* estimator (CS). Middle panel reports analogous results estimated using OLS and continuous treatment (number of wells). All 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, and cluster standard errors at the circle level. Continuous variables are transformed using the inverse hyperbolic since function. 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)	0.010	0.003	0.019	0.010	0.019	0.001	0.022	0.007	0.013	-0.005
St. Error	(0.009)	(0.021)	(0.013)	(0.027)	(0.012)	(0.008)	(0.017)	(0.010)	(0.012)	(0.028)
p-val	0.266	0.877	0.137	0.712	0.116	0.900	0.201	0.453	0.302	0.867
Coef. (DID)	0.001	0.006	0.002	0.001	-0.002	0.001	0.001	0.003	0.000	0.005
St. Error	(0.003)	(0.004)	(0.003)	(0.006)	(0.003)	(0.002)	(0.004)	(0.002)	(0.003)	(0.005)
p-val	0.672	0.128	0.558	0.875	0.602	0.567	0.805	0.274	0.963	0.363
n (CS)	27,611	27,431	27,465	27,227	27,608	27,598	27,593	27,591	27,576	26,962
n (DID)	27,924	27,744	27,779	27,537	27,920	27,911	27,906	27,904	27,889	27,284
DV Mean	63.0	10.9	21.3	17.4	12.5	32.1	30.9	13.4	40.4	9.2

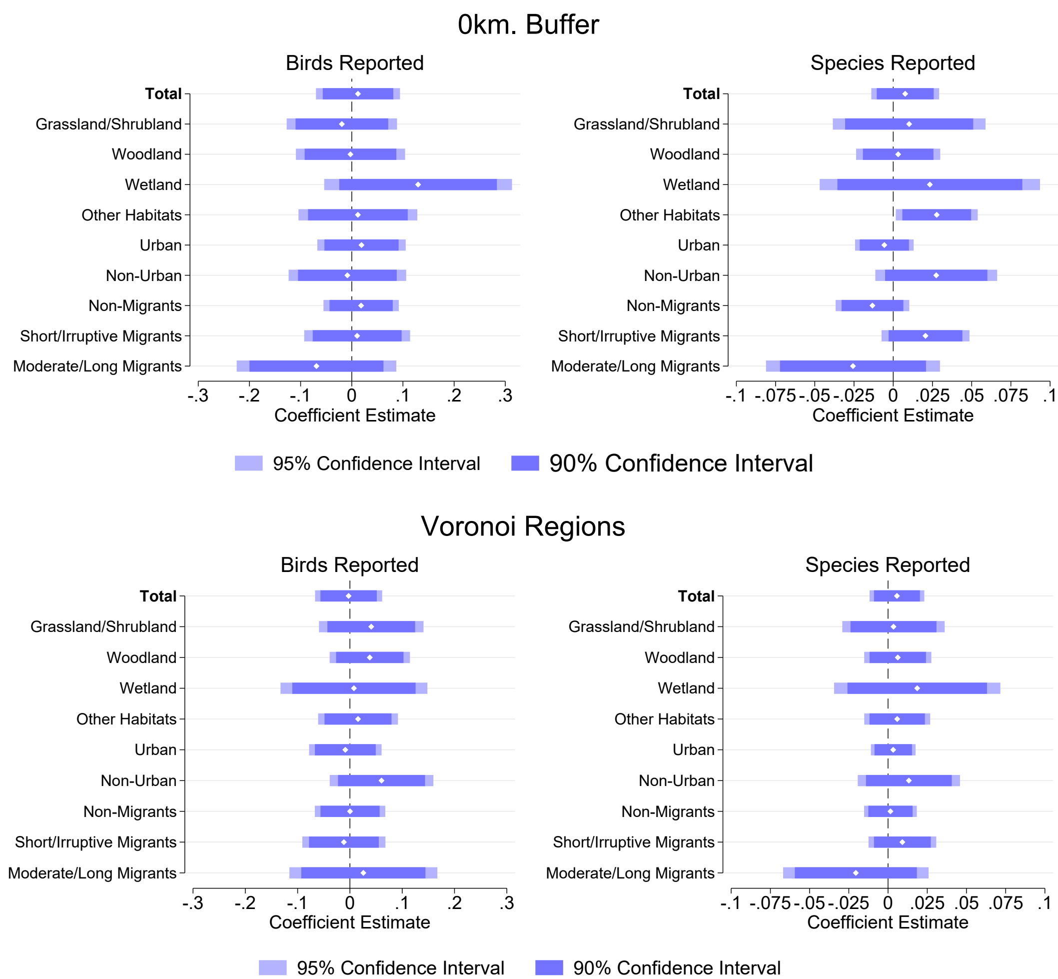
Note: Refer to note under Table A3.

Figure A7: Shale Oil and Gas Treatment: Robustness to Alternative Buffer Zones



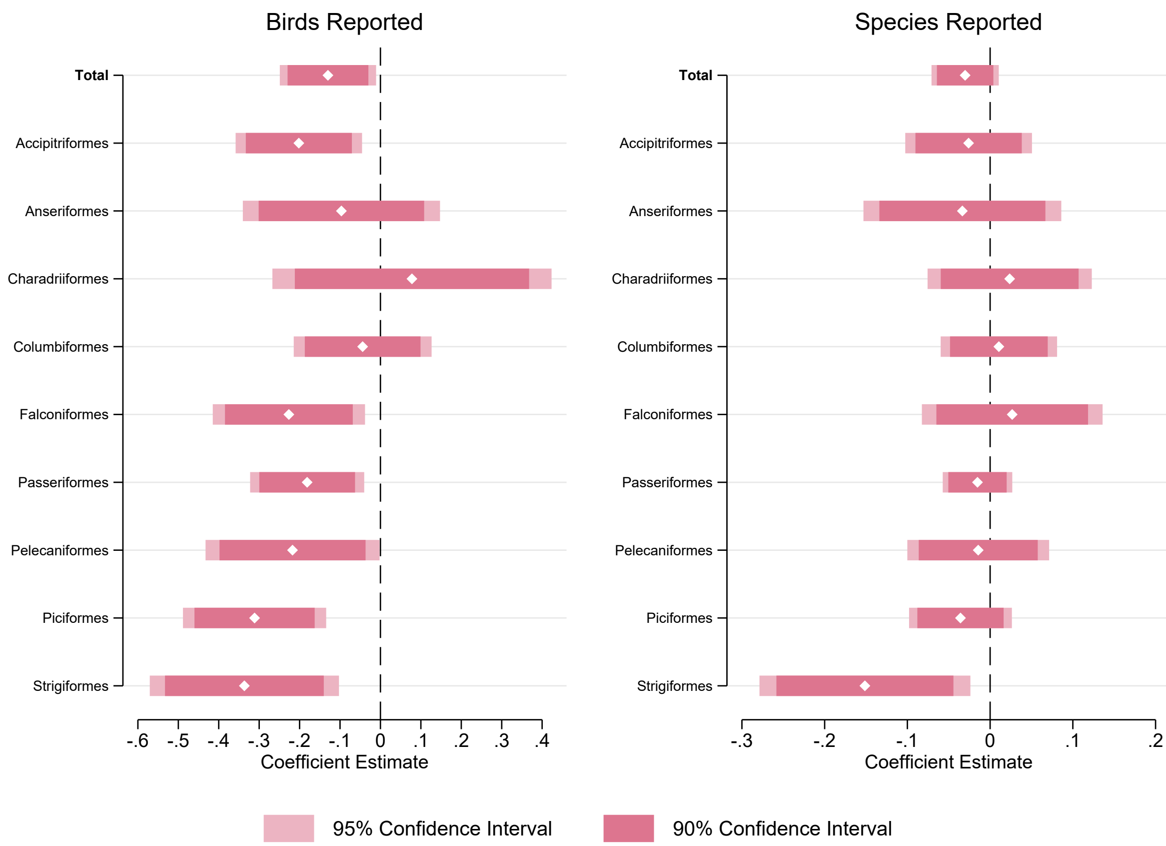
Note: Figures are organized analogously to Figure 4. Top figures use an alternative treatment definition wherein circles are treated in and after the year shale wells are first drilled within the strict boundaries of a CBC circle. This definition assumes no spillover effects from nearby shale wells. 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. These tessellations create mutually exclusive regions covering the entire lower-48 United States, with all the points inside a region closer to their circle centroid than to any other centroid. Importantly, the x-axes in top and bottom figures are not set equal to each other, nor to the axis in Figure 4, and visual comparisons should be made with caution. The preferred specification (5km. spillover buffer) and both robustness checks yield similar point estimates. The 0km. buffer results in less precise estimates due to reduced sample size and no accounting for spillover effects. Voronoi regions result in even more significantly negative estimates, including across-the-board negative effects on species diversity.

Figure A8: Wind Energy Treatment: Robustness to Alternative Buffer Zones



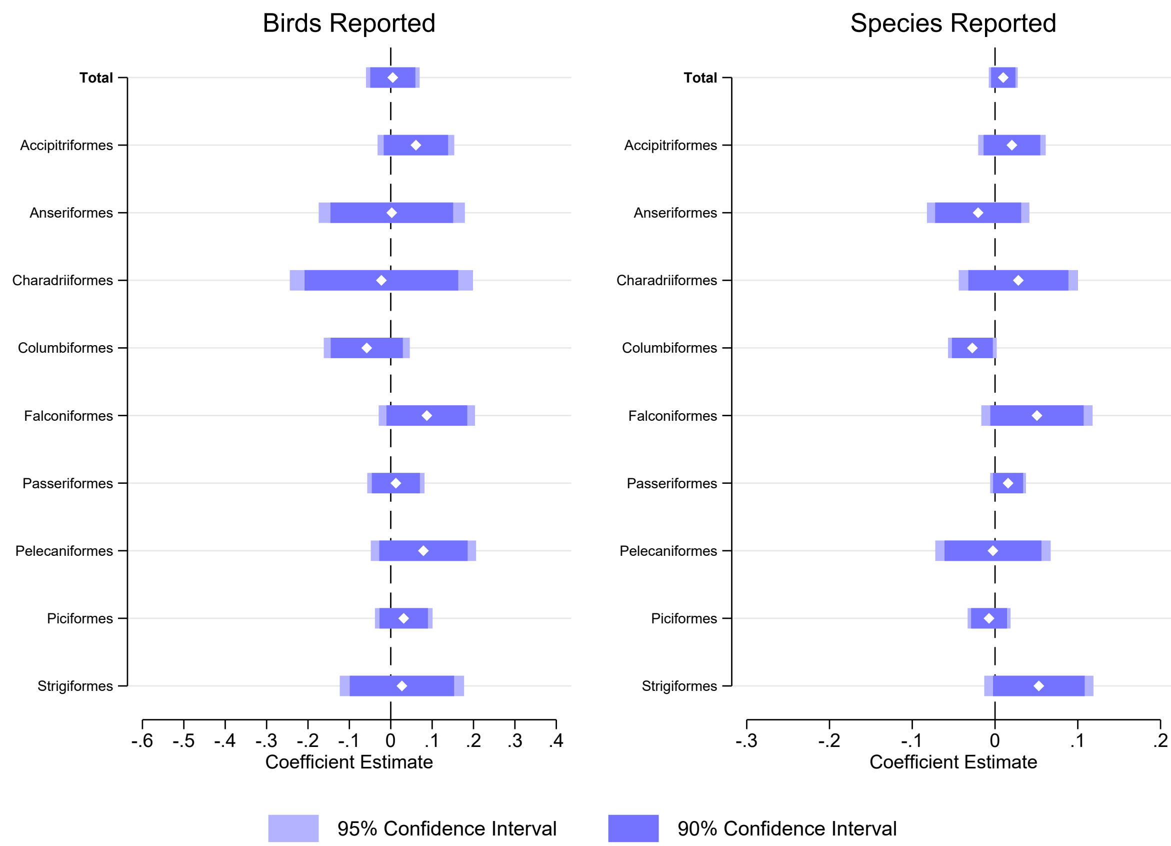
Note: Figures are organized analogously to Figure 5. Top figures use an alternative treatment definition wherein circles are treated in and after the year wind turbines are first installed within the strict boundaries of a CBC circle. This definition assumes no spillover effects from nearby turbines. Bottom figures use a treatment definition wherein circles are treated in and after the year wind turbines are first installed within the Voronoi tessellation around a CBC circle centroid. These tessellations create mutually exclusive regions covering the entire lower-48 United States, with all the points inside a region closer to their circle centroid than to any other centroid. Importantly, the x-axes in top and bottom figures are not set equal to each other, nor to the axis in Figure 5, and visual comparisons should be made with caution. The preferred specification (5km. spillover buffer) and both robustness checks yield similar point estimates and standard errors, reflecting the consistency of wind turbine treatment effect estimates of approximately zero, or in some cases, slightly positive.

Figure A9: 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 A10: 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

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

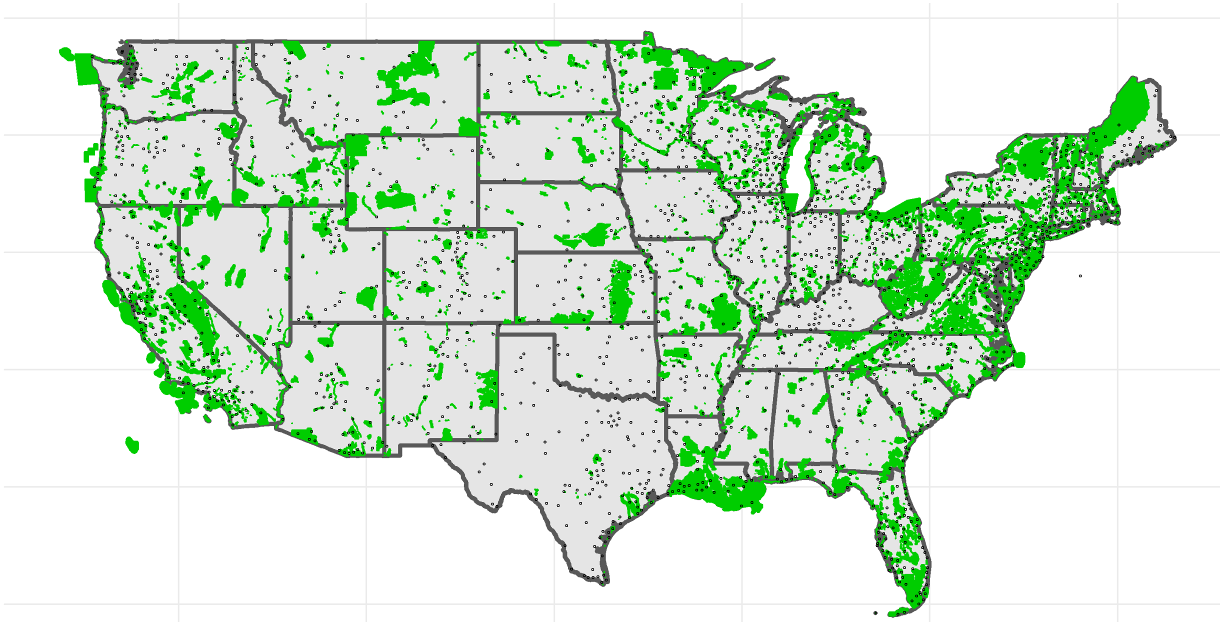
Source: National Audubon Society (2022)

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

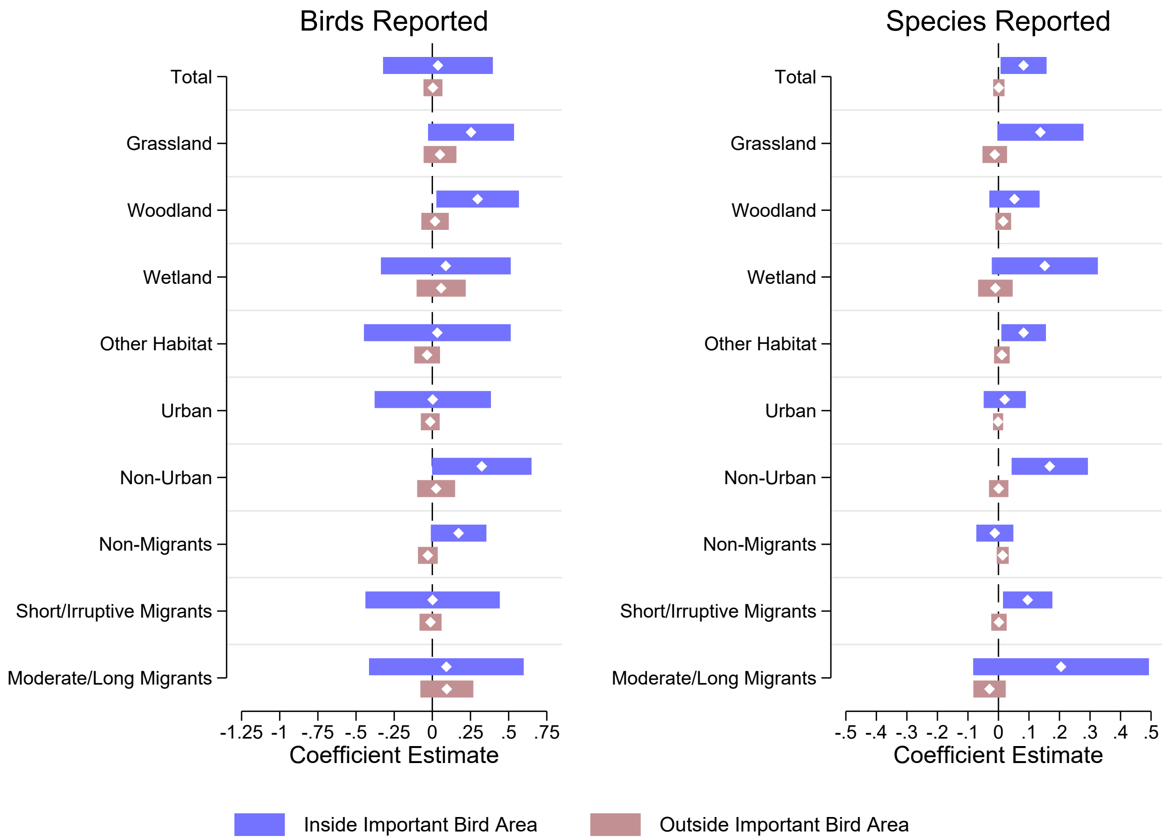
Note: Upper two panels report coefficient estimates, standard errors, and p-values, as well as sample sizes and baseline dependent variable means, for regression of human population in CBC circle's county on relative time indicators around the year of shale well or wind turbine arrival, using Callaway 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 A11: CBC Circle Locations Relative to Important Bird Areas (in Green)



Source: National Audubon Society (2023).

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 time indicators around the year wind turbines were first installed 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 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. Continuous outcomes are transformed using the inverse hyperbolic since function.