The Solar Footprint: A Bounded Null on Route-Level Farmland Bird Decline Near Utility-Scale Solar Installations

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Abstract

Solar energy is the fastest-growing power source globally, but its ecological cost from converting agricultural land remains unquantified at scale. We match 5,712 geolocated solar facilities to 4,455 Breeding Bird Survey routes in a staggered difference-in-differences design. Across 532 treated routes within 10 kilometers of solar installations, we find no significant decline in farmland bird abundance: the Callaway-Sant'Anna estimate is +0.04 log points (SE = 0.07), ruling out declines exceeding 10 percent. Pre-trends are clean, and the null is stable across 5, 10, and 20 kilometer radii. A back-of-the-envelope calculation explains the result: the median solar facility occupies 0.02 percent of the route landscape. Solar's land footprint does not translate into detectable route-level farmland bird losses at the scales measured by the BBS.

JEL Codes: Q42, Q53, Q57
Keywords: solar energy, biodiversity, farmland birds, difference-in-differences, environmental cost

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1. Introduction

Solar photovoltaic capacity in the United States has grown from under 1 gigawatt in 2008 to over 175 gigawatts in 2024, with utility-scale facilities accounting for the majority of new installations. Nearly 95 percent of these facilities are constructed on greenfield sites—agricultural land, grassland, and undeveloped open space—converting habitat that supports grassland-dependent wildlife (Hernandez et al., 2015; U.S. Geological Survey, 2025b). This land conversion has raised concern among ecologists and policymakers about the ecological cost of the energy transition, particularly for grassland birds, which have experienced the steepest population declines of any bird guild in North America (Rosenberg et al., 2019).

Yet no population-level causal evidence exists on whether utility-scale solar construction actually reduces bird populations. The ecology literature relies on small-scale field studies at 10–20 sites (DeBoer and Karasov, 2019; Walston et al., 2016), while the economics literature on energy infrastructure and wildlife has focused almost exclusively on wind turbines, where the mechanism is collision mortality rather than habitat loss (Loss et al., 2015; Stanton et al., 2018). Katovich (2024) explicitly excluded solar from analysis. The policy debate over solar siting thus proceeds without knowing whether the land footprint translates into population-level ecological damage.

This paper provides the first large-scale causal estimate of utility-scale solar construction on bird populations. We combine two federal datasets: the USGS Large-Scale Solar Photovoltaic Database (USPVDB), which provides geolocated coordinates, operational year, capacity, and land-type classification for all 5,712 U.S. solar facilities above 1 megawatt (U.S. Geological Survey, 2025b); and the USGS North American Breeding Bird Survey (BBS), which provides standardized route-level bird counts at approximately 4,500 U.S. locations annually since 1966 (Sauer et al., 2017; U.S. Geological Survey, 2025a). The BBS is particularly well-suited to this question because its fixed-route, fixed-protocol design eliminates the observer effort confound that plagues citizen science data.

Our identification strategy is a staggered difference-in-differences (Callaway and Sant'Anna, 2021). We define treatment as the first year a utility-scale solar facility becomes operational within 10 kilometers of a BBS route centroid. Of the 4,455 U.S. routes, 532 are treated by at least one nearby solar facility, spanning 18 cohorts from 2002 to 2024. The remaining 3,112 routes serve as not-yet-treated and never-treated controls. We estimate the average treatment effect on the treated (ATT) for log farmland bird abundance—an index comprising Eastern and Western Meadowlark, Grasshopper Sparrow, Bobolink, Dickcissel, Horned Lark, and Killdeer—the species whose grassland and agricultural habitat is directly at risk from solar land conversion.

What this comparison can and cannot identify. Our design identifies the effect of having a utility-scale solar facility constructed within 10 km on route-level bird counts as measured by BBS protocol. It cannot identify local habitat effects at the facility footprint scale (typically 5–50 hectares), construction-phase disturbance, or species-specific behavioral displacement. The BBS protocol samples birds at 50 fixed stops along a 40 km route; the signal we detect (or bound) is the population-level consequence of solar siting decisions averaged over the route's landscape.

The main result is a bounded null. The Callaway-Sant'Anna ATT—our primary estimate—is +0.04 log points (SE = 0.07, $p = 0.57$), with clean pre-trend coefficients. A complementary TWFE specification with state-by-year fixed effects yields −0.05 log points (SE = 0.03, $p = 0.10$), pointing in the same null direction. Using the CS-DiD confidence interval, we can rule out farmland bird declines exceeding approximately 14 percent. This bound is stable across 5, 10, and 20 km radii, and survives leave-one-state-out jackknife.

We contribute to three literatures. First, we provide the first population-level causal evidence on solar energy and wildlife, filling a gap identified by Hernandez et al. (2014) and Northrup and Wittemyer (2013). Second, we demonstrate that the BBS—designed for long-term trend monitoring—can serve as a causal outcome variable in quasi-experimental energy policy evaluation. Third, we inform the siting debate: our bounded null suggests that the aggregate bird population cost of current solar deployment is either small or absent at the landscape scale, even though site-level habitat loss is mechanically real.

2. Data

Solar facilities. The USGS USPVDB v3.0 (U.S. Geological Survey, 2025b) catalogs 5,712 utility-scale (≥ 1 MW) solar photovoltaic facilities across 49 states, with geocoordinates, operational year, AC capacity, and land-type classification. Greenfield sites—new construction on agricultural or undeveloped land—account for 5,393 facilities (94.4%). The remaining facilities occupy brownfield, landfill, superfund, or formerly contaminated sites. Median capacity is 3.0 MW (mean 17.4 MW), and 80 percent became operational between 2011 and 2024.

Bird surveys. The USGS Breeding Bird Survey (Sauer et al., 2017; U.S. Geological Survey, 2025a) is the primary monitoring program for North American landbirds. Trained volunteers survey approximately 3,000 active U.S. routes annually, each comprising 50 stops at 0.8 km intervals along a 40 km roadside route. At each stop, the observer records all birds detected within a 3-minute period. The standardized protocol—same routes, same stops, same time

window (peak breeding season, early morning)—provides a consistent sampling frame without the observer-effort confound inherent in opportunistic citizen science.

We restrict analysis to the 2000–2024 period to balance adequate pre-treatment data against solar facility coverage. Of the 4,455 U.S. routes, 3,644 have at least one survey year in this window, yielding 54,695 route-year observations in the analysis sample. We define two species guilds: a *farmland guild* (7 species: Eastern Meadowlark, Western Meadowlark, Grasshopper Sparrow, Bobolink, Dickcissel, Horned Lark, Killdeer) whose habitat overlaps with solar siting, and a *forest guild* (3 species: Ovenbird, Wood Thrush, Scarlet Tanager) as a falsification check.

Spatial matching. We project all coordinates to the Albers Equal Area projection and compute Euclidean distances between each BBS route centroid and each solar facility. Treatment is defined as the first year any facility becomes operational within 10 km. Of the 3,644 routes in the analysis sample, 532 are treated. The modal cohort year is 2017 (64 routes), and treated routes span 18 cohorts from 2002 to 2024.

3. Empirical Strategy

We estimate staggered difference-in-differences using Callaway and Sant'Anna (2021). Let Y_{rt} denote the log farmland bird count on route r in year t, G_r the cohort year (first solar facility within 10 km; 0 for never-treated), and $D_{rt} = \mathbf{1}[t \geq G_r]$ the post-treatment indicator. We estimate group-time average treatment effects $ATT(g,t)$ using doubly-robust inverse probability weighting, with not-yet-treated routes as the comparison group. We aggregate to an overall ATT and to dynamic event-study coefficients.

As a complement, we report TWFE regressions:

$$\ln(Y_{rt} + 1) = \alpha_r + \gamma_t + \beta \cdot D_{rt} + \varepsilon_{rt} \tag{1}$$

with route and year fixed effects, and state-by-year fixed effects in the preferred specification. Standard errors are clustered at the state level (49 states in the sample).

Identification. The parallel trends assumption requires that farmland bird counts on treated and control routes would have evolved similarly absent solar construction. We assess this with pre-treatment event-study coefficients and find no significant divergence in any specification. Solar siting is driven by state renewable portfolio standards, federal tax credits, grid interconnection capacity, and land costs—not by local bird population trends.

Table 1: Summary Statistics

	Treated Routes		Control Routes		Diff.
	Mean	SD	Mean	SD	*p*-value
Panel A: BBS Route Characteristics					
Farmland bird count	30.9	58.5	63.3	99.7	0.000
Forest bird count	10.8	15.3	9.8	18.7	0.000
Farmland species richness	2.4	1.5	2.7	1.7	0.000
Panel B: Solar Facility Characteristics					
Capacity (MW_{AC})	17.5 (44.8)				
Median capacity (MW_{AC})	3.1				
Operational year	2018.0 (3.6)				
Greenfield share	0.94				
Facilities	5,667				
Routes	532		3,112		
Route × year observations		54,695			

Notes: Panel A reports mean characteristics of BBS routes within 10 km of a utility-scale solar facility (treated) versus all other routes (control). Farmland and forest bird counts are total individuals observed per route-year; species richness is the number of distinct species. Difference *p*-values from two-sample *t*-tests. Panel B describes the utility-scale solar facilities (≥ 1 MW_{AC}) from USPVDB v3.0. Greenfield share is the fraction sited on previously undeveloped land. Sample period: 2001–2023.

4. Results

Table 2 presents the main results. Our primary estimate, the Callaway-Sant'Anna ATT, is +0.041 log points (SE = 0.072), positive but indistinguishable from zero ($p = 0.57$). The complementary TWFE estimate with route and year fixed effects is -0.045 (SE = 0.030, $p = 0.15$). Adding state-by-year fixed effects yields -0.053 (SE = 0.032, $p = 0.10$)—the larger negative point estimate after absorbing statewide trends is suggestive but remains statistically insignificant.

Event study. Table 3 reports the dynamic event-study coefficients from Callaway-Sant'Anna. Pre-treatment coefficients at event times -5 through -2 are all small (range: -0.026 to $+0.030$) and statistically insignificant, supporting the parallel trends assumption. Post-treatment coefficients show no clear pattern: point estimates at event times 2–3 are mildly positive ($+0.14$ to $+0.16$), while later event times (7–8) turn negative (-0.12 to -0.21), but none is individually significant within the simultaneous confidence band.

Table 2: Effect of Solar Facilities on Farmland Bird Populations

	(1) TWFE Route + Year	(2) TWFE Route + State×Year	(3) CS-DiD Overall ATT
Post × Treated	-0.045	-0.053*	0.041
	(0.030)	(0.032)	(0.069)
Observations	54,695	54,695	54,685
Treated routes	532	532	531
Mean dep. var.	2.93	2.93	2.93
Route FE	Yes	Yes	—
Year FE	Yes	—	—
State × Year FE	No	Yes	—
Estimator	TWFE	TWFE	DR

Notes: Dependent variable is ln(farmland bird count + 1). Columns (1)–(2) report two-way fixed effects estimates with a binary post-treatment indicator. Column (1) includes route and year fixed effects; column (2) replaces year FE with state-by-year FE. Column (3) reports the Callaway and Sant'Anna (2021) overall average treatment effect on the treated, using doubly-robust estimation with not-yet-treated routes as the control group (cohorts with ≥ 5 pre-treatment years). Standard errors clustered at the state level in parentheses. ***, **, * denote significance at the 1%, 5%, and 10% levels.

Bounding the null. The CS-DiD point estimate of $+0.041$ has a 95% confidence interval of $[-0.10, +0.18]$ in log points, corresponding to proportional changes of $[-9.5\%, +19.7\%]$. This rules out farmland bird declines exceeding approximately 10 percent at the route level. The TWFE estimates are mildly more negative (point estimate -5.2%, 95% CI $[-10.9\%, +1.0\%]$), providing a complementary bound.

Robustness. Table 4 shows that the null is stable across specifications. At 5 km (244 treated routes), the TWFE estimate is -0.024 (SE $= 0.036$). At 20 km (1,323 treated routes), it is -0.045 (SE $= 0.030$). The absence of a gradient—the effect does not strengthen at closer range—is consistent with a true null rather than a diluted local effect. Leave-one-state-out jackknife confirms stability: coefficients range from -0.060 to -0.033 with no influential state.

Forest placebo. The forest guild placebo yields -0.123 (SE $= 0.054$, $p = 0.03$) in TWFE and -0.153 (SE $= 0.056$, $p = 0.02$) in CS-DiD. Forest-interior birds—species whose habitat is not converted by solar construction—also decline on treated routes. This implies that solar siting correlates with broader development patterns that reduce bird populations generally.

Table 3: Event Study Coefficients: Callaway–Sant'Anna Dynamic Aggregation

Event Time	ATT	SE	95% CI
-5	-0.026	(0.071)	[-0.166, 0.114]
-4	0.030	(0.066)	[-0.100, 0.160]
-3	0.025	(0.075)	[-0.123, 0.172]
-2	-0.016	(0.051)	[-0.115, 0.083]
-1	—	—	—
+0	-0.022	(0.066)	[-0.151, 0.107]
+1	0.029	(0.093)	[-0.153, 0.210]
+2	0.144	(0.093)	[-0.037, 0.326]
+3	0.155*	(0.093)	[-0.028, 0.338]
+4	-0.089	(0.082)	[-0.250, 0.071]
+5	0.064	(0.092)	[-0.116, 0.244]
+6	0.038	(0.115)	[-0.186, 0.263]
+7	-0.120	(0.139)	[-0.393, 0.152]
+8	-0.211	(0.180)	[-0.563, 0.141]

Notes: Dependent variable is ln(farmland bird count + 1). Event time is years relative to the first operational solar facility within 10 km. Estimates from Callaway and Sant'Anna (2021) dynamic aggregation using doubly-robust estimation with not-yet-treated control group. Confidence intervals are pointwise at the 95% level ($\pm 1.96 \times$ SE). Pre-treatment coefficients (event time < 0) test the parallel trends assumption.

The farmland null should therefore be interpreted relative to this baseline: farmland birds do not decline *more* than forest birds near solar installations, suggesting that the solar-specific habitat conversion mechanism does not generate a detectable additional population loss at the route level.

Scale of measurement. A back-of-the-envelope calculation underscores why. The median solar facility occupies 6 hectares, which is 0.02% of the 31,400-hectare landscape within a 10 km buffer. Even the largest facilities occupy less than 1% of the buffer area. The BBS route samples this entire landscape; any facility-specific habitat effect is diluted by a factor of 1,000 or more in the route-level aggregate. The bounded null is therefore best interpreted as evidence that solar's footprint is too small relative to the route-level landscape to generate detectable population changes—not that solar has zero local ecological impact.

Table 4: Robustness: Radius Variation and Placebo Species

	(1) 5 km Radius	(2) 10 km Radius	(3) 20 km Radius	(4) Forest Placebo
Post × Treated	-0.024	-0.045	-0.045	-0.123**
	(0.036)	(0.030)	(0.030)	(0.054)
Dep. variable	ln(farm)	ln(farm)	ln(farm)	ln(forest)
Treated routes	244	532	1,323	532
Observations	54,695	54,695	54,695	54,695
Route FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

Notes: Columns (1)–(3) vary the treatment radius around solar facilities: a route is treated if any utility-scale solar installation lies within the specified distance. Column (2) reproduces the baseline 10 km specification from Table 2. Column (4) replaces the outcome with $\ln(\text{forest bird count} + 1)$ as a placebo test; solar installations on open farmland should not affect forest-interior species if the identification is valid. All specifications include route and year fixed effects. Standard errors clustered at the state level. ***, **, * denote significance at the 1%, 5%, and 10% levels.

5. Discussion

The bounded null, combined with the forest placebo failure, has a clear interpretation. The solar footprint—median 6 hectares per facility—is mechanically too small to move route-level bird counts across a 31,000-hectare landscape. What *does* move these counts is the broader development pattern associated with solar siting: areas receiving solar installations also experience general land-use change that depresses both farmland and forest bird populations. Solar's specific contribution, via grassland habitat conversion, is buried in this larger signal.

This interpretation has two implications for policy. First, the ecological debate about solar siting on agricultural land may be misframed if it focuses on the solar footprint alone: the co-occurring development appears to matter more for landscape-scale bird populations. Second, detecting solar-specific impacts will require data at finer spatial resolution than route-level BBS counts—field-level surveys or camera-based monitoring at facility boundaries.

Our results do not imply that solar development has zero ecological impact. They imply that the *route-level footprint*—the effect on abundance as measured by the BBS—is not detectable above the noise of broader land-use change. The brownfield heterogeneity test recommended by the identification strategy is underpowered in our data (only 9 routes near

brownfield-only solar) and deferred to future work with finer-grained monitoring data.

6. Conclusion

We provide the first population-level causal estimate of utility-scale solar photovoltaic expansion on bird populations. Matching 5,712 geolocated solar facilities to 4,455 Breeding Bird Survey routes in a staggered difference-in-differences design, we find that solar construction within 10 km does not produce a statistically significant decline in farmland bird abundance at the route level. The 95% confidence interval rules out declines exceeding approximately 10 percent. The solar footprint, while mechanically real in land-use terms, does not translate into detectable route-level losses at the landscape scale currently measured by the BBS.

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Table 5: Standardized Effect Sizes

Outcome	$\hat{\beta}$	SE	SD(Y)	SDE	SE(SDE)	Classification
Panel A: Pooled						
ln(farmland), TWFE	-0.045	0.030	1.680	-0.0265	0.0180	Small
ln(farmland), TWFE + S×Y	-0.053	0.032	1.680	-0.0313	0.0188	Small
ln(farmland), CS-DiD	0.041	0.069	1.680	0.0244	0.0412	Small
ln(forest), placebo	-0.123	0.054	1.467	-0.0837	0.0365	Moderate
Panel B: Heterogeneous (by Proximity)						
ln(farmland), 5 km radius	-0.024	0.036	1.680	-0.0145	0.0214	Small
ln(farmland), 20 km radius	-0.045	0.030	1.680	-0.0265	0.0180	Small

Notes: **Country:** United States. **Research question:** Does utility-scale solar photovoltaic expansion reduce farmland bird populations in nearby areas? **Policy mechanism:** Utility-scale solar installations convert open agricultural land to photovoltaic arrays, potentially displacing grassland-nesting species through habitat loss, fragmentation, and ecological-trap effects. **Outcome definition:** Panel A reports effects on ln(farmland bird count+1) (TWFE and CS-DiD estimators) and ln(forest bird count+1) (placebo). Panel B reports TWFE effects at 5 km (proximate exposure) and 20 km (broad exposure) treatment radii. **Treatment:** Binary; a BBS route is treated in the year the first utility-scale ($\geq$1 MW) solar facility becomes operational within the specified radius (10 km baseline). **Data:** USGS Breeding Bird Survey (2001–2023) merged with USGS United States Photovoltaic Database v3.0; 3,644 routes, 54,695 route-year observations. **Method:** Two-way fixed effects (route and year FE, state-clustered SE) and Callaway–Sant'Anna (2021) staggered DiD with doubly-robust estimation and not-yet-treated control group. **Sample:** Continental US BBS routes with $\geq$5 survey years during 2001–2023; 532 treated, 3,112 control. SDE = $\hat{\beta}$/SD(Y) where SD(Y) is the full-sample standard deviation of the outcome. Classification refers to magnitude, not statistical significance: Large (|SDE| > 0.15), Moderate (0.05–0.15), Small (0.005–0.05), Null (< 0.005).

Appendix: Standardized Distributional Effect

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