

Nonlinear survey-effort adjustment removes the reported bird-diversity effect

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Abstract

A recent study published in *Science* reported that greater photovoltaic policy stringency (PSI) was associated with lower Shannon diversity, lower Simpson diversity, lower species richness, and slightly higher species evenness in China. We exactly reproduced the published model and then evaluated seven alternative survey-effort specifications across Richness, Shannon diversity, Simpson diversity, and Evenness. Existing reanalyses incorporated additional measures of birdwatching effort but retained the original **Duration** variable, which is derived from total observation time and observer number. We found that once these two effort dimensions were represented explicitly, PSI became statistically indistinguishable from zero for all four biodiversity measures. Retaining Duration contributed little additional information and produced coefficient patterns that were difficult to interpret ecologically. Nonlinear representations of total observation time and observer participation substantially improved model fit, whereas additional nonlinear flexibility in environmental controls and PSI provided little benefit. A semi-spline specification containing nonlinear effort terms but linear PSI and environmental controls was consistently selected by the Bayesian Information Criterion (BIC) across all four biodiversity measures. Under this preferred specification, the reported PSI associations were no longer statistically detectable. These findings indicate that the reported biodiversity effect is highly sensitive to survey-effort specification and that nonlinear survey-effort adjustment provides a substantially better description of the observation process.

Keywords: photovoltaic policy; bird diversity; citizen science; survey effort; biodiversity monitoring; nonlinear modelling; biodiversity metrics; Bayesian Information Criterion

Introduction

Zhang et al. (2026) reported that greater photovoltaic policy stringency (PSI) was associated with lower Shannon diversity, lower Simpson diversity, lower species richness, and slightly higher species evenness. Their study has prompted extensive discussion and several formal reanalyses concerning citizen-science data quality, the explanatory importance of PSI, and the representation of birdwatching effort (Chen et al., 2026; Ding et al., 2026; Han, 2026; Lai and Zhang, 2026; Li and Wang, 2026).

The original study represented survey effort using

$$\text{Duration} = \log(BT/BN + 1),$$

where BT is total birdwatching time and BN is the number of birdwatchers within a county-month. This ratio compresses two distinct dimensions of survey effort into a single quantity. Consequently, observation processes of very different scale can receive identical effort adjustments. For example, a county-month with one birdwatcher contributing 10 observation hours and another with 10 birdwatchers contributing 100 observation hours both have $BT/BN = 10$ and therefore receive the same Duration value. However, the latter represents substantially greater observer participation and total observation effort and would likely record a greater number of species and individuals.

Several recent reanalyses showed that the reported PSI associations disappear when additional measures of birdwatching effort are included in the model (Chen et al., 2026; Ding et al., 2026; Han, 2026; Li and Wang, 2026). However, all of these analyses retained the original Duration variable, even when total observation time and observer number were represented explicitly. Because Duration is a deterministic function of BT and BN , specifications containing all three terms include overlapping representations of the same survey-effort process and may yield coefficients that are difficult to interpret ecologically.

A further concern is functional form. Relationships between observed biodiversity and survey effort are unlikely to remain linear, even after logarithmic transformation, because additional observation hours and observers should exhibit diminishing or otherwise nonlinear returns in species detection. Although previous reanalyses considered alternative survey-effort variables and specifications (Chen et al., 2026; Ding et al., 2026; Han, 2026; Li and Wang, 2026), none formally evaluated whether nonlinear representations of survey effort provide a better-supported description of the observation process.

We therefore reanalysed the published data to determine whether Duration adequately represents survey effort, whether retaining Duration after explicitly representing total observation time and observer participation is necessary, and whether nonlinear survey-effort adjustment is better supported by the data. To assess the robustness of the reported conclusions, we evaluated seven alternative specifications across four biodiversity dimensions: Richness, Shannon diversity, Simpson diversity, and Evenness.

Methods

We used the authors' publicly released replication data and reproduced their baseline regression, including the published merge sequence, transformations, 1st-to-99th-percentile winsorisation, county fixed effects, year-month fixed effects, and county-clustered standard errors. Evenness was calculated as Shannon diversity divided by log richness, following Zhang et al. (2026). We fitted seven specifications to each response: (1) no survey-effort variable; (2) the original Duration model; (3) Duration plus linear $\log(BT + 1)$ and $\log(BN + 1)$, as in previous reanalyses; (4) linear $\log(BT + 1)$ and $\log(BN + 1)$ without Duration; (5) natural cubic splines with five degrees of freedom for $\log(BT + 1)$ and $\log(BN + 1)$, while PSI and all remaining controls were retained in linear form (preferred semi-spline model); (6)

splines for the two effort variables and all other continuous controls, with linear PSI; and (7) splines for PSI, the effort variables, and all continuous controls. Models 3 and 4 evaluated whether Duration provided additional information once total observation time and observer participation were represented explicitly. Because Duration is a deterministic function of these two variables, Models 5 to 7 omitted Duration and instead progressively evaluated whether nonlinear representations of total observation time, observer participation, the remaining continuous controls, and PSI improved model performance. Analyses were conducted in R using the packages *fixest* and *splines*.

Results

We exactly reproduced the fully adjusted specification reported by Zhang et al. (2026), obtaining a PSI coefficient estimate of -0.012528 ($SE = 0.003655$), compared with the published estimate of -0.0125 ($SE = 0.0037$). We also reproduced the reported negative associations between PSI and species richness and Simpson diversity, together with the reported positive association between PSI and species evenness (Fig. 1; Tables 1–4).

The original Duration specification reproduced the conclusions reported by Zhang et al. (2026). Under this specification, PSI coefficients were negative for Richness, Shannon diversity, and Simpson diversity, and positive for Evenness. The associations were statistically significant for Richness and Shannon diversity, marginally significant for Simpson diversity, and significantly positive for Evenness. Once total observation time and observer participation were represented explicitly through $\log(BT + 1)$ and $\log(BN + 1)$, however, PSI became statistically indistinguishable from zero for all four biodiversity measures, regardless of whether Duration was retained, removed, or the two effort variables were represented using natural cubic splines (Fig. 1). The reported negative associations with Richness, Shannon diversity, and Simpson diversity, together with the reported positive association with Evenness, were therefore not robust to explicit representation of the two survey-effort dimensions.

The largest improvement in model fit occurred when $\log(BT + 1)$ and $\log(BN + 1)$ were added to the original Duration model. This specification substantially increased within- R^2 across all four biodiversity measures, from 0.050 to 0.583 for Richness, from 0.040 to 0.180 for Shannon diversity, from 0.019 to 0.062 for Simpson diversity, and from 0.001 to 0.045 for Evenness (Fig. 2). Removing Duration while retaining the two linear effort variables produced almost identical PSI estimates and within- R^2 values, indicating that Duration contributed little information once total observation time and observer participation were represented explicitly.

The next largest improvement occurred when the two linear effort variables were replaced by natural cubic splines. Within- R^2 increased from 0.582 to 0.595 for Richness, from 0.179 to 0.232 for Shannon diversity, from 0.061 to 0.115 for Simpson diversity, and from 0.044 to 0.051 for Evenness. Applying spline functions to all remaining controls, and subsequently to PSI, produced only small additional gains. Across all four biodiversity measures, the semi-spline specification, which represented total observation time and observer participation nonlinearly while retaining linear PSI and environmental controls, consistently achieved the lowest **Bayesian Information Criterion (BIC)** values (Table 5).

Discussion

We reanalysed the data and code released by Zhang et al. (2026) to evaluate whether the reported biodiversity associations depended on the representation of survey effort. Specifically, we compared seven alternative survey-effort specifications across Richness, Shannon diversity, Simpson diversity, and Evenness, including models with separate measures of total observation time and observer participation, as well as nonlinear representations of these effort variables. Our results show that the reported PSI associations disappear once total observation time and observer participation are represented explicitly and that a semi-spline model of these two effort dimensions is consistently preferred by **Bayesian Information Criterion (BIC)**.

The primary modelling issue in the original study appears to be the representation of survey effort rather than photovoltaic policy intensity itself. The original study represented survey effort using a single variable,

$$Duration = \log(BT/BN + 1),$$

where BT is total birdwatching time and BN is the number of birdwatchers. This ratio compresses two distinct dimensions of survey effort into a single quantity. Consequently, very different observation processes can receive identical effort adjustments. For example, a county-month with one birdwatcher and 10 total observation hours and another with 10 birdwatchers and 100 total observation hours both have $BT/BN = 10$ and therefore receive the same Duration value, despite representing substantially different levels of observer participation and total observation effort. Because the biodiversity responses are calculated from records pooled across all observations within a county-month, this loss of information may be consequential.

Several recent reanalyses showed that the reported PSI associations disappear when additional measures of birdwatching effort are included (Chen et al., 2026; Ding et al., 2026; Han, 2026; Li and Wang, 2026). However, all of these analyses retained the original Duration variable while simultaneously including one or both of the variables from which it is derived. As a result, overlapping representations of the same survey-effort process were estimated in the same model. Our results indicate that this specification produces coefficient patterns that are difficult to interpret ecologically. For Richness, Duration is significantly negative whereas both total observation time and observer number are significantly positive. For Shannon and Simpson diversity, observer number remains strongly positive, whereas total observation time becomes negative or statistically insignificant. For Evenness, coefficient signs differ substantially depending on whether Duration is included. Such instability is expected when several highly related transformations of the same underlying process are estimated simultaneously. Importantly, removing Duration while retaining separate measures of total observation time and observer participation has almost no effect on either the PSI

coefficient or model fit, indicating that Duration contributes little information once its constituent variables are represented explicitly.

We further show that linear adjustment for survey effort is inadequate. Explicit treatment of observation effort and detectability is widely recommended when analysing citizen-science biodiversity data (Kelling et al., 2019; Johnston et al., 2021; Kozak et al., 2026). Flexible smooth functions are likewise widely used when ecological relationships are expected to be nonlinear and difficult to specify *a priori* (Wood, 2017).

The largest improvement in model fit occurred when total observation time and observer participation were introduced explicitly. The next largest improvement occurred when these two effort variables were represented nonlinearly. For example, within- R^2 for Shannon diversity increased from 0.179 under the linear effort model to 0.232 under the semi-spline specification. Similar improvements were observed for Richness, Simpson diversity, and Evenness. By contrast, allowing nonlinear representations for all remaining environmental controls, and subsequently for PSI itself, produced only negligible additional gains. Thus, the principal functional-form deficiency appears to lie in the representation of survey effort rather than in PSI or the remaining environmental covariates.

The model comparison results support this interpretation. Once separate measures of total observation time and observer participation are included, the reported PSI associations disappear across all four biodiversity measures. Additional flexibility applied specifically to these two effort variables substantially improves model fit. However, additional nonlinear flexibility in environmental controls and PSI contributes little further explanatory power. Consistent with this pattern, the semi-spline specification containing nonlinear effects for **BT and BN**, but linear representations of PSI and the remaining controls, is consistently selected by the **Bayesian Information Criterion (BIC)** across Richness, Shannon diversity, Simpson diversity, and Evenness.

Zhang et al. (2026) interpreted the combination of declining richness and increasing evenness as evidence of environmental filtering, whereby habitat simplification removes specialised species while leaving a smaller but more evenly distributed community. Under the BIC-preferred specification, however, neither the decline in richness nor the increase in evenness remains statistically detectable. The reported negative associations with Shannon and Simpson diversity are likewise absent. These findings do not imply that photovoltaic development has no ecological consequences. Rather, they indicate that the statistical evidence supporting the reported biodiversity response is highly sensitive to survey-effort specification.

Conclusion

In the Zhang et al. (2026) study, the original Duration ratio assigns the same effort value to county-months with substantially different total observation time and observer participation. Adding the two underlying effort dimensions, total observation time and observer number, removes the reported PSI associations, but retaining all three variables produces coefficients that are difficult to interpret ecologically. Modelling total observation time and observer

participation separately and nonlinearly substantially improves model fit and is consistently preferred by the **Bayesian Information Criterion (BIC)**.

Under this preferred specification, the reported negative associations with Richness, Shannon diversity, and Simpson diversity, together with the reported positive association with Evenness, are no longer statistically detectable. The available evidence therefore does not robustly support the conclusion that greater photovoltaic policy intensity reduced bird diversity. Instead, our results indicate that inference regarding photovoltaic policy stringency (PSI) depends critically on how survey effort is represented and that nonlinear adjustment for total observation time and observer participation provides a substantially better description of the observation process.

Acknowledgements

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Data and Code Availability

The original data and Stata code were obtained from the replication archive released by Zhang et al. (2026). The R code used to reproduce all analyses, figures, and tables reported in this study is archived in Mendeley Data (Liu, 2026; DOI: 10.17632/s6xmr7nt3d.1).

Use of Artificial Intelligence

During the preparation of this manuscript, Microsoft Copilot was used to assist with language editing, translation of publicly available Stata code into R, code troubleshooting, and discussion of alternative statistical modelling approaches. The AI system was not used to generate primary scientific results. All data preparation, statistical analyses, model selection, numerical results, interpretations, and final manuscript content were independently reviewed and verified by the author, who takes full responsibility for the work.

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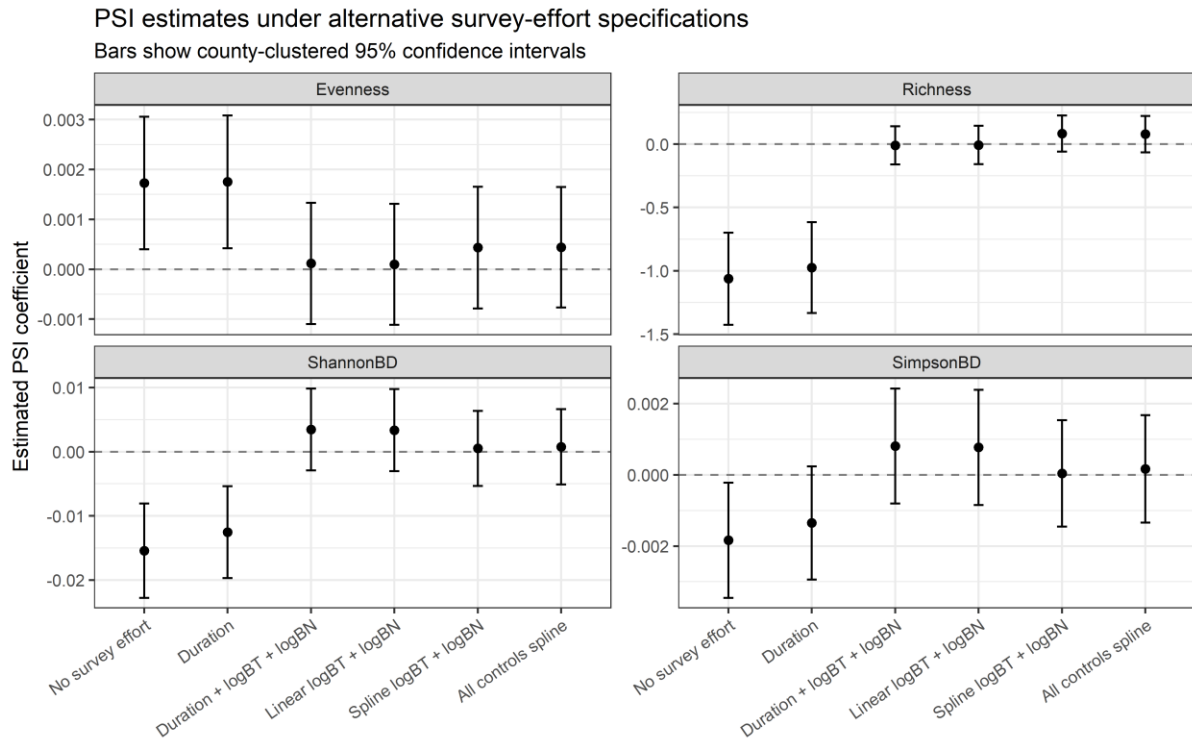


Figure 1. PSI estimates under alternative survey-effort specifications for four biodiversity measures. Points show PSI coefficient estimates and bars show county-clustered 95% confidence intervals. Richness, Shannon diversity, and Simpson diversity were negatively associated with PSI under the original Duration specification, whereas Evenness was positively associated with PSI. Once total observation time and observer participation were represented explicitly, the PSI estimates became statistically indistinguishable from zero across all four biodiversity measures.

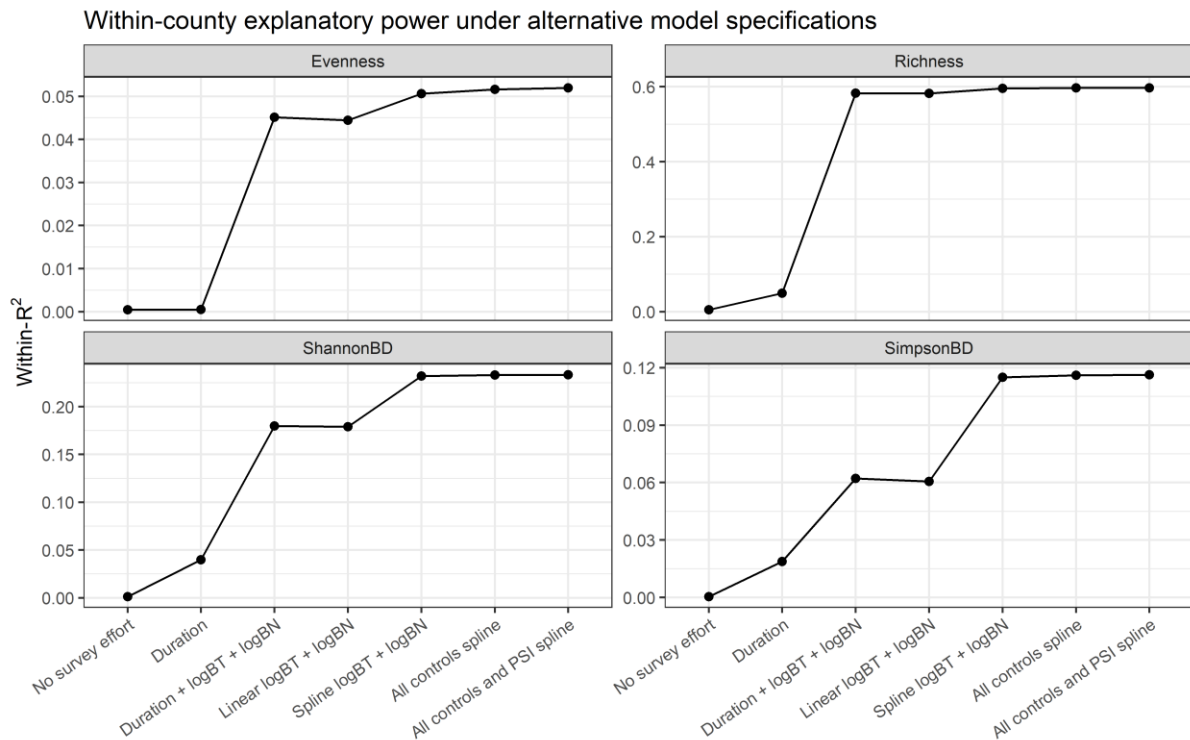


Figure 2. Within-county explanatory power under seven survey-effort specifications for four biodiversity measures. Within- R^2 increased most when total observation time and observer participation were added to the original Duration model. The next largest improvement occurred when these two effort variables were represented using natural cubic splines. Additional nonlinear flexibility in environmental controls and PSI produced only small further gains.

Table 1. Association between bird diversity (Shannon diversity) and photovoltaic policy intensity (PSI) under alternative birdwatching-effort specifications. The dependent variable is Shannon diversity. Columns compare the original Duration specification, the three-effort specification used in previous reanalyses, separate linear representations of total observation time and observer participation, and the preferred semi-spline specification. Other control variables follow Zhang et al. (2026). County-clustered standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. For the semi-spline model, total observation time and observer participation were represented using natural cubic splines with five degrees of freedom. Because individual spline coefficients are not directly interpretable, the table reports the joint significance of the spline terms rather than the coefficients of individual spline basis functions.

Variable	Duration	Duration + logBT + logBN	logBT + logBN	Spline logBT + logBN
PSI	0.0125*** (0.0037)	0.0035 (0.0033)	0.0034 (0.0033)	0.0005 (0.0030)
Duration	0.1638*** (0.0057)	0.1312*** (0.0233)		
logBT		-0.0049 (0.0209)	0.1115*** (0.0049)	***
logBN		0.4985*** (0.0258)	0.3697*** (0.0101)	***
Controls	YES	YES	YES	YES
Year-month				
FE	YES	YES	YES	YES
County FE	YES	YES	YES	YES
Observations	46,371	46,371	46,371	46,371
Adjusted-R ²	0.2999	0.4019	0.4014	0.4399
Within-R ²	0.0398	0.1798	0.179	0.232

Table 2. Association between bird diversity (Simpson diversity) and photovoltaic policy intensity (PSI) under alternative birdwatching-effort specifications. The dependent variable is Simpson diversity. Columns compare the original Duration specification, the three-effort specification used in previous reanalyses, separate linear representations of total observation time and observer participation, and the preferred semi-spline specification. Other control variables follow Zhang et al. (2026). County-clustered standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. For the semi-spline model, total observation time and observer participation were represented using natural cubic splines with five degrees of freedom. Because individual spline coefficients are not directly interpretable, the table reports the joint significance of the spline terms rather than the coefficients of individual spline basis functions.

Variable	Duration	Duration + logBT + logBN	logBT + logBN	Spline logBT + logBN
PSI	-0.0014 (0.0008)	0.0008 (0.0008)	0.0008 (0.0008)	0.0000 (0.0008)
Duration	0.0274*** (0.0013)	0.0466*** (0.0057)		
logBT		-0.0223*** (0.0050)	0.0190*** (0.0011)	***
logBN		0.0911*** (0.0062)	0.0453*** (0.0023)	***
Controls	YES	YES	YES	YES
Year-month				
FE	YES	YES	YES	YES
County FE	YES	YES	YES	YES
Observations	46,371	46,371	46,371	46,371
Adjusted-R ²	0.1631	0.2001	0.1987	0.245
Within-R ²	0.0187	0.0622	0.0605	0.1149

Table 3. Association between bird diversity (Richness) and photovoltaic policy intensity (PSI) under alternative birdwatching-effort specifications. The dependent variable is Richness. Columns compare the original Duration specification, the three-effort specification used in previous reanalyses, separate linear representations of total observation time and observer participation, and the preferred semi-spline specification. Other control variables follow Zhang et al. (2026). County-clustered standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. For the semi-spline model, total observation time and observer participation were represented using natural cubic splines with five degrees of freedom. Because individual spline coefficients are not directly interpretable, the table reports the joint significance of the spline terms rather than the coefficients of individual spline basis functions.

Variable	Duration	Duration + logBT + logBN	logBT + logBN	Spline logBT + logBN
PSI	0.9741*** (0.1828)	-0.0093 (0.0770)	-0.0070 (0.0772)	0.0830 (0.0727)
Duration	5.1489*** (0.1960)	-2.8763*** (0.8697)		
logBT		5.3340*** (0.7986)	2.7845*** (0.1347)	***
logBN		22.3218*** (0.9524)	25.1447*** (0.3878)	***
Controls	YES	YES	YES	YES
Year-month				
FE	YES	YES	YES	YES
County FE	YES	YES	YES	YES
Observations	46,371	46,371	46,371	46,371
Adjusted-R ²	0.4596	0.7628	0.7625	0.7698
Within-R ²	0.0495	0.5828	0.5824	0.5952

Table 4. Association between bird diversity (Evenness) and photovoltaic policy intensity (PSI) under alternative birdwatching-effort specifications. The dependent variable is Evenness. Columns compare the original Duration specification, the three-effort specification used in previous reanalyses, separate linear representations of total observation time and observer participation, and the preferred semi-spline specification. Other control variables follow Zhang et al. (2026). County-clustered standard errors are reported in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. For the semi-spline model, total observation time and observer participation were represented using natural cubic splines with five degrees of freedom. Because individual spline coefficients are not directly interpretable, the table reports the joint significance of the spline terms rather than the coefficients of individual spline basis functions.

Variable	Duration	Duration + logBT + logBN	logBT + logBN	Spline logBT + logBN
PSI	0.0018** (0.0007)	0.0001 (0.0006)	0.0001 (0.0006)	0.0004 (0.0006)
Duration	0.0013 (0.0008)	0.0211*** (0.0037)		
logBT		-0.0148*** (0.0034)	0.0038*** (0.0007)	***
logBN		-0.0318*** (0.0040)	-0.0524*** (0.0017)	***
Controls	YES	YES	YES	YES
Year-month				
FE	YES	YES	YES	YES
County FE	YES	YES	YES	YES
Observations	46,371	46,371	46,371	46,371
Adjusted-R ²	0.1905	0.2266	0.2261	0.2309
Within-R ²	0.0005	0.0451	0.0445	0.0506

Table 5. Bayesian Information Criterion (BIC) values for seven alternative survey-effort specifications across four biodiversity measures. BIC values are reported for Richness, Shannon diversity, Simpson diversity, and Evenness under the seven model specifications described in the Methods. Smaller BIC values indicate stronger support after accounting for model complexity. The minimum BIC value for each biodiversity measure is shown in **bold**. The semi-spline specification, which represents total observation time and observer participation using natural cubic splines while retaining linear PSI and environmental controls, consistently achieved the lowest BIC value across all four biodiversity measures.

No	Model	Evenness	Richness	ShannonBD	SimpsonBD
1	No survey effort	-21262.05	444964.51	139128.03	7789.18
2	Duration	-21254.81	442899.29	137312.69	6942.96
3	Duration + logBT + logBN	-23239.63	405367.25	130028.31	4864.93
4	Linear logBT + logBN	-23219.79	405403.48	130061.12	4935.82
5	Spline logBT + logBN	-23419.19	404071.48	127053.20	2254.96
6	All controls spline	-23123.53	404248.90	127327.74	2539.54
7	All controls and PSI spline	-23095.60	404285.32	127357.85	2572.75