Received: 9 August 2021 | Accepted: 14 July 2022

DOI: 10.1002/2688-8319.12173

Ecological Solutions and Evidence | BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Confirmation that eagle fatalities can be reduced by automated curtailment of wind turbines

Christopher J. W. McClure[1] | Brian W. Rolek[1] | Leah Dunn[1] | Jennifer D. McCabe[1] | Luke Martinson[2] | Todd E. Katzner[3]

[1]The Peregrine Fund, Boise, Idaho, USA

[2]Western EcoSystems Technology, Cheyenne, Wyoming, USA

[3]U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, Boise, Idaho, USA

Correspondence
Christopher J. W. McClure, The Peregrine Fund, 5668 West Flying Hawk Lane, Boise, ID 83709, USA.
Email: cmcclure@peregrinefund.org

Handling Editor: Natasha Gownaris

Funding information
M.J. Murdock Charitable Trust

Abstract

1. Automated curtailment is potentially a powerful technique to reduce collision mortality of wildlife with wind turbines. Previously, we used a before–after–control–impact framework to demonstrate that eagle fatalities declined after automated curtailment was implemented with the IdentiFlight system at a wind power facility in Wyoming, USA. We received substantial interest and feedback regarding our study and, here, we implement several analytical suggestions and include more recent data that strengthen the inference we draw from our results.
2. The five main analytical suggestions we received were to (1) exclude from analysis data that were collected during the period when automated curtailment was only partially implemented; (2) only analyse data from a single make and model of turbine; (3) evaluate changes in the rate of fatality, instead of the yearly numbers of fatalities that result from fluctuations around that rate; (4) calculate a standard measure determining effects of a treatment in a before–after–control–impact study and (5) examine yearly fluctuations of the fatality rate during the before period.
3. After incorporating these suggestions and including additional data collected since the prior paper was published, our results confirm prior work. We demonstrate that eagle fatalities were reduced by 85% (95% highest density interval = 12%, 100%) after implementation of automated curtailment. Rate of fatalities declined by 2.85 eagles per year (−0.67, 5.70) between before and after periods at the treatment site and increased by 2.26 eagles per year (−1.77, 7.37) at the control site. Overall, the fatality rate declined by 4.91 (−0.27, 11.27) more eagles per year at the treatment site than at the control site. The probability that the fatality rate declined at the treatment site relative to the control site was 0.97.
4. Our re-analysis strengthens our inference by using more robust analyses and data to support the conclusions of the prior study suggesting that automated curtailment was effective at reducing eagle fatalities at our treatment site. Because of the

site- and species-specific nature of our work, future research should examine the efficacy of automated curtailment at other sites, with other species, and under different curtailment regimes.

KEYWORDS
bald eagle, curtailment, golden eagle, IdentiFlight, mitigation, renewable energy, wind power, wind turbine

1 | INTRODUCTION

Automated curtailment is a technique to reduce wildlife collision mortality whereby wind turbines are stopped or slowed automatically when wildlife are considered at risk of collision (McClure, Rolek, Dunn, et al., 2021). Although promising, automated curtailment incurs financial costs, from installation of sophisticated detection technology and increased number of curtailments that result in reduced energy production (Allison et al., 2019). The efficacy of automated curtailment therefore must be thoroughly tested if managers of wind facilities are to effectively balance the costs associated with mitigating wildlife mortality while also maximizing energy production.

We recently evaluated the ability of IdentiFlight, a camera-based automated curtailment system, to mitigate collision mortality of bald (*Haliaeetus leucocephalus*) and golden eagles (*Aquila chrysaetos*) at a wind facility in Wyoming, USA (McClure, Rolek, Dunn, et al., 2021). IdentiFlight is designed to detect eagles, determine whether they are at risk of collision with specific wind turbines and, if so, curtail those individual turbines (McClure et al., 2018). In that study (McClure, Rolek, Dunn, et al., 2021), we compared the change in counts of eagle fatalities between time periods before and after the implementation of automated curtailment at a treatment site to changes at a nearby control site, at which curtailment measures were not implemented. We demonstrated that the number of fatalities declined substantially at the treatment site after implementation of automated curtailment. In total, our analysis showed that the number of eagle fatalities declined by 82% (75%–89%) at the treatment site relative to the control site (McClure, Rolek, Dunn, et al., 2021).

Our study generated substantial interest, including feedback regarding potential improvements, and suggestions for follow-up analyses of new data to ensure the robustness of our inference and that the efficacy of automated curtailment is maintained over time (CJWM and TEK, personal observation). The suggestions we received centred on five refinements of study design: (1) more intuitive demarcation of the before and after periods of our experiment; (2) more even comparison of the turbine types at the treatment and control sites; (3) focusing on the rate, rather than the number, of fatalities; (4) calculating the standard measure of a before–after–control–impact (BACI) analysis and (5) examining yearly fluctuations of the fatality rate during the before period.

Regarding the first refinement, in the original study we used the date of activation of the first automated curtailment units at the treatment site as the demarcation between before and after periods at the control site. The treatment was therefore not fully implemented during the entire after period (Figure 1a) and this could obscure our inference. Regarding the second refinement, our control site had 66 General Electric (GE) model GE1.5-77 turbines, whereas our treatment site had 66 of the same model turbines in addition to 44 Siemens model SWT-2.3-101 turbines. It could be argued that a better comparison would be between the 66 GE turbines at each site, and that exclusion of data from the Siemens turbines at the treatment site would be more straightforward. In this way, we could compare two sites with the exact same number of identical turbines, and any differences in fatality rates among turbine types would be controlled. Regarding the third refinement, we calculated the number of fatalities before and after installation of automated curtailment, but we did not estimate the underlying fatality rate (λ). This is analogous to observing differences between the outcomes of rolls of two weighted dice versus calculating the underlying probabilities that each die would land on a given side. In the original study, changes in the number of fatalities between time periods could therefore be due to random fluctuations around a mean λ. An improved analysis therefore would focus on changes in λ under a BACI framework, providing stronger inference into whether automated curtailment lowers fatality rates. Also, in our original study, we calculated an estimate of percent change that is rarely used to report the effects of BACI experiments. An improvement to doing this is to calculate the measure proposed by Chevalier et al. (2019) for use in BACI studies, to compare λ between sites as well as between time periods. This standard metric, termed the BACI Contrast, allows for a more intuitive and conventional comparison of BACI results.

Finally, there was concern that the decrease in fatalities we observed might simply be due to random fluctuations in eagle fatalities from collisions with wind turbines. In our previous analysis (McClure, Rolek, Dunn, et al., 2021), we demonstrated that more eagles were killed at the treatment site during the before period than the control site, whereas during the after period fewer eagles were killed at the treatment site relative to the control site. If the control site is frequently more deadly than the treatment site, then the change regarding which site is deadliest is unlikely to be due to automated curtailment. However, the switch to the control site being deadlier might be attributed to automated curtailment if during the before period the treatment site was consistently deadlier than the control site. One way to address this concern would be to examine λ during each of the

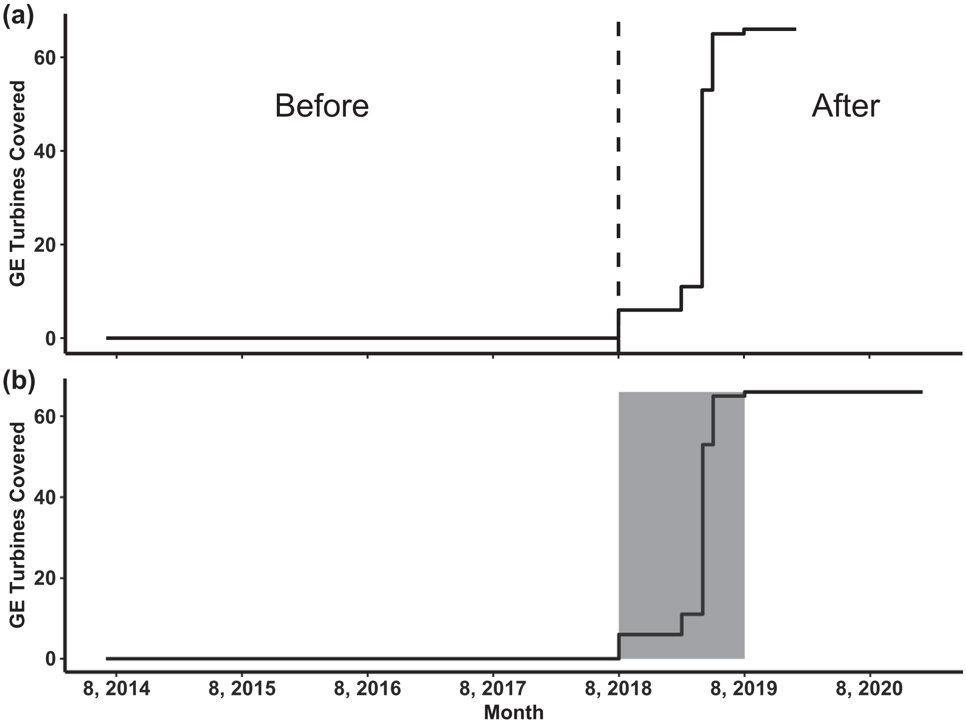

FIGURE 1 Graphical representation of the coverage of automated curtailment at our Wyoming study site. Shown are the number of General Electric (GE) turbines at our treatment being controlled (i.e. covered) by automated curtailment units over the course of the pervious (McClure, Rolek, Dunn, et al., 2021) (a) and current (b) studies. In panel (a), the dashed line at 8, 2018 depicts the demarcation between before and after periods in the previous study. In panel (b), the grey box depicts the time period during which automated curtailment was being installed. Data from this time period were not analysed in the current study. Thus, the grey box represents the demarcation between before and after periods

4 years before implementation of automated curtailment to determine how the fatality rates of the two sites were related to each other.

Although none of these suggestions reveal fatal flaws in our past work, we agree that implementing these changes to the analysis would provide stronger and more intuitive inference regarding the efficacy of automated curtailment for reducing wildlife mortalities at this site. As such, here, we implement the suggested improvements with additional data. Specifically, we compare the fatality rate (λ) using data only from GE turbines and we exclude data from 1 August 2018 to 13 August 2019, the period during which automated curtailment was incrementally being implemented across the facility (Figure 1). We also calculate the BACI Contrast (Chevalier et al., 2019) to gauge the effect of our treatment on λ. Finally, we examine λ during the before period to determine if there were differences in this metric between the control site and the treatment site. Implementing these changes also provides an opportunity to add data collected since the original paper was published. We therefore included additional data from 2020 to determine whether λ remained low at the treatment site during this full year under automated curtailment.

2 | MATERIALS AND METHODS

Field technicians collected data regarding carcass persistence and searcher efficiency and observed fatalities at both the control (Campbell Hill Windpower Project) and nearby (~ 15 km) treatment (Top of the World Windpower Project) sites. Both sites were located within Converse County, WY, USA, and were operated by Duke Energy. Search methods were identical to those described by McClure, Rolek, Dunn, et al. (2021). Turbines were searched every 30 days both during the before and after periods at the treatment site and during the before period at the control site. During the after period at the control site, turbines were searched every 56 days, except the period between August and October 2020, when searches were suspended for health and safety reasons. We directly specified the search interval length to account for variation in search intervals. All appropriate permits were obtained from the U.S. Fish and Wildlife Service for our field work.

2.1 | Analysis

We give an overview of our analysis strategy here, with details below. We first calculated the detection probabilities of eagle carcasses, and their associated uncertainty, for before and after periods at each site. We then used these estimates, along with the numbers of observed fatalities, to estimate the yearly fatality rate (λ), with associated error estimates, for each site-by-time-period combination. Finally, in addition to the percent change as calculated in our previous work, we calculated the BACI Contrast to determine the reduction in the fatality rate that might be attributed to automated curtailment implemented by IdentiFlight.

The IdentiFlight system is flexible in that it can be programmed for site-specific curtailment criteria. During our study, the curtailment regime used two virtual concentric cylinders to define threshold criteria. The radii of the cylinders began as 200 m (inner) and 400 m (outer) on 1 August 2018, but on 22 August 2018 were changed to 150 m (inner) and 350 m (outer). The heights of the inner and outer virtual cylinders were 200 and 400 m, respectively, throughout the entire study. Curtailment was never ordered if an object identified as an eagle was outside of the outer cylinder. Curtailment was always ordered when that object was identified as an eagle (≥90% confidence) and it entered the inner cylinder. Between the two cylinders, IdentiFlight estimated a time to collision threshold based on the speed and trajectory of the purported eagle. The time to collision threshold was originally set to 10 s, but was changed to 15 s in September 2019. See McClure et al. (2018), McClure, Rolek, Dunn, et al. (2021), and McClure, Rolek, Braham, et al. (2021) for further details regarding the study site and the configuration and programming of the IdentiFlight system.

We used GenEst (Dalthorp et al., 2018, 2020; Simonis et al., 2018) in R (R Development Core Team, 2018) to calculate the detection probability of eagle carcasses (for details on our approach, see McClure, Rolek, Dunn, et al., 2021). For all detection analyses, we assumed searcher efficiently was constant no matter how long a carcass had been in the field ($k = 1$; McClure, Rolek, Dunn, et al., 2021). This assumption risks overestimating detection probability. However, we also tested setting $k = 0.6$ and inference was unaffected. We tested for seasonal effects in both carcass persistence and searcher efficiency by fitting models with seasonal factors (i.e. a factor indicating Spring, Summer, Winter, and Fall). We used Akaike's information criterion (Akaike, 1974) corrected for small sample size (AICc; Hurvich & Tsai, 1989) to compare seasonal models with intercept-only models. We considered there to be seasonal effects of detection probability if the seasonal models had the lowest AICc value (McClure, Rolek, Dunn, et al., 2021). When seasonal effects were present, we estimated detection probability by season; otherwise, we estimated it by year. We used the estgGeneric() function in GenEst to incorporate the AICc-best models of searcher efficiency and carcass persistence into estimates of detection probability. We used the median across all posterior draws as the point estimate of detection probability and the upper and lower limits of the 95% highest density interval (HDI; Makowski et al., 2019) as the confidence interval. These estimates of the distribution of detection probability, per site and treatment, allowed us to calculate α and β parameters of a Beta distribution using the parameter conversion tool in Evidence of Absence software (EoA; Dalthorp et al., 2017)

Next, we used the α and β parameters from a Beta distribution along with the observed numbers of fatalities to estimate the posterior distribution of fatality rate by site and treatment type. Doing this allows us to incorporate the estimate of detection probability and its uncertainty into the estimate of fatality rate. We calculated this estimate with the posteriorLpdf.ab() function in EoA with the default prior. This function incorporates the detection probability into estimates of λ. Specifically, EoA estimates the posterior distribution of λ, given a carcass count (X) and the estimate of detection probability ($\hat{g}$) as $P(\lambda|X,\hat{g}) = \frac{P(X|\lambda,\hat{g})P(\lambda)}{\int P(X|\lambda,\hat{g})P(\lambda)d\lambda}$, where $X \sim \text{binomial}(M, \hat{g})$, $M|(\lambda) \sim \text{Poisson}(\lambda)$ and $\hat{g} \sim \text{beta}(Ba, Bb)$, where Ba and Bb are parameters characterizing the distribution of $\hat{g}$ (Dalthorp et al., 2017).

EoA outputs the dimensions of a curve for posteriors. We used the approx() function in R to obtain, for each site and time period combination, 1000 draws from under the curves outputted from EoA. Using these draws, we then estimated the fatality rates (λ) per site and time period. We performed this procedure—instead of simply using the basic functions of EoA—because, by performing calculations across all draws of posterior distributions, we were able to propagate the uncertainty in λ per site and time period into the calculations below. We calculated the fatality rate that we would expect at the treatment site during the after period in the absence of automated curtailment as $E\lambda_{\text{Treatment, After}} = \frac{\lambda_{\text{Control, After}}}{\lambda_{\text{Control, Before}}} \times \lambda_{\text{Treatment, Before}}$ (May et al., 2020). Then, we calculated the percent reduction in λ that might be attributed to automated curtailment using the formula: $1 - \frac{\lambda_{\text{Treatment, After}}}{E\lambda_{\text{Treatment, After}}} \times 100$.

Finally, we calculated the metric suggested by Chevalier et al. (2019) to compare BACI sites and time periods—the BACI Contrast. The BACI Contrast quantifies the difference in λ due to automated curtailment and was calculated as $(\lambda_{\text{Treatment, After}} - \lambda_{\text{Treatment, Before}}) - (\lambda_{\text{Control, After}} - \lambda_{\text{Control, Before}})$. We calculated this measure across the 1000 draws of posteriors of λ. In this setting, a negative value of the BACI Contrast would indicate that the fatality rate (λ) decreased more at the treatment site than the control site—thus suggesting efficacy of automated curtailment—and a positive value would suggest the opposite.

We used the median and the upper and lower limits of the 95% HDI of these calculations across all draws to estimate the central tendency of parameter estimates and to determine confidence in our estimates. We also calculated the probability of direction (pd; Makowski et al., 2019) for each measure as the proportion of draws greater or less than zero.

To compare λ at the treatment and control sites prior to implementation of automated curtailment, we calculated λ yearly at both sites. For this analysis, we considered a year to last from 1 August to 31 July, which matches the data collection period of the study and the implementation schedule of automated curtailment (Figure 1). To estimate λ yearly, we performed a similar procedure as above, but could not estimate a yearly detection probability because of data scarcity within years. We therefore used the detection probabilities calculated per site and time period (before and after) to correct the yearly rates. Thus, for the years beginning in August of 2014, 2015, 2016 and 2017, we used detection probabilities from the before period, whereas for the year beginning August 2019 we used detection probabilities from the after period.

3 | RESULTS

Detection probabilities for all treatment-by-site combinations varied by season (model selection tables and seasonal detection rates are in Tables S1–S3). Median detection probabilities for the before periods

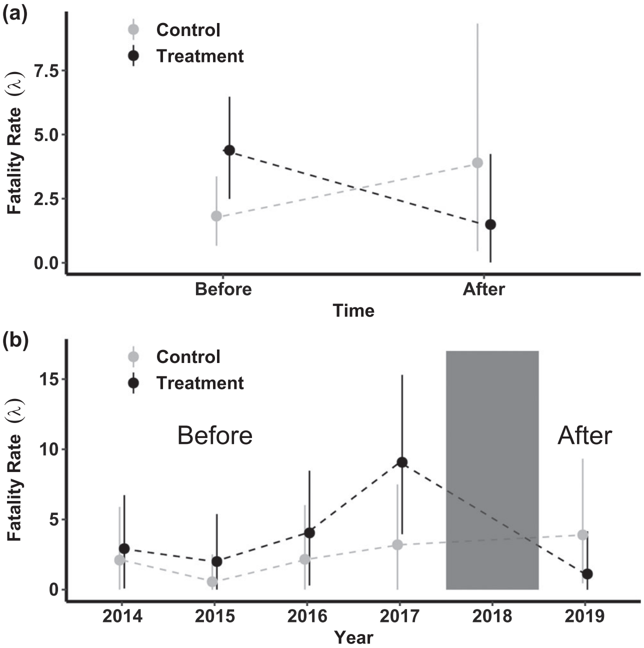

FIGURE 2 (a) Median fatality rate (λ, ± 95% CI) of eagles per year at the control and treatment sites in Wyoming, USA, before (September 2014 to August 2018) and after (August 2019 to January 2021) full implementation of automated curtailment. (b) Yearly fatality rate (λ, ± 95% CI) of eagles at the control and treatment sites in Wyoming, USA. Each year began in 1 August and ended 31 July of the succeeding calendar year. The grey rectangle during 2018 represents the period during which automated curtailment units were being installed at the treatment site. Data collected during this installation period were not considered for analysis

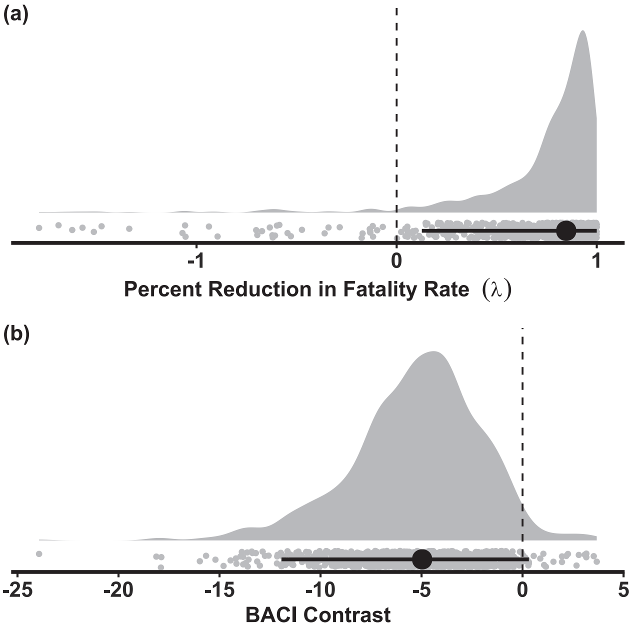

FIGURE 3 Raincloud plots (Allen et al., 2019) depicting the distribution of (a) the percent reduction in the fatality rate (λ) and (b) the before–after–control–impact (BACI) Contrast. Grey points represent individual draws of the distributions, while half-violin plots depict the distribution of the points and the point ranges represent the medians and the 95% highest density intervals of the points

at the control and treatment sites were 0.92 (95% HDI = 0.70, 1.00) and 0.96 (0.93, 0.99), respectively. During the after period, the median was 0.74 (0.40, 0.93) at the control site and 0.90 (0.65, 0.99) at the treatment site.

Before automated curtailment was implemented, during the period from 1 August 2014 to 31 July 2018, there were 18 eagle carcasses found under GE turbines at the treatment site and seven found at the control site. After automated curtailment was implemented, from the period starting on 14 August 2019 until 31 December 2020, there were two eagle carcasses found at the treatment site and four found at the control site. Of these, one eagle was found under GE turbines at the treatment site in 2020, while two were found at the control site (these 2020 data were not presented in McClure, Rolek, Dunn, et al., 2021).

During the before period, the estimated median annual fatality rate at the treatment site was 2.55 eagles per year (0.08, 5.14) greater than at the control site (median treatment = 4.48; 2.63, 6.63; median control = 1.84; 0.60, 3.31; Figure 2). The probability of direction (pd) for this difference was 0.98—indicating a high probability that the fatality rate was greater at the treatment site during the before period. However, once automated curtailment was fully implemented, the median annual fatality rate was similar or lower at the treatment site (1.54; 0.00, 4.18) than at the control site (3.92; 0.76, 8.79; Figure 2). The median difference between the two sites during the after period was −2.30, although the HDI for this difference was wide (−7.78, 2.29) and the probability of direction was lower (0.85).

Put differently, after automated curtailment was fully implemented at the treatment site, the median difference in λ from before to after periods was −2.85 eagles (−5.70, 0.67). The probability that this change was <0 was high (pd = 0.95). In contrast, λ at the control site was relatively steady or increased from the before to the after period (median difference = 2.26 eagles; −1.77, 7.37; Figure 1). The probability that this change was >0 was lower (pd = 0.86). Given the annual fatality rates (λ's) presented above at the treatment site relative to the control site, there was an 85% (12%, 100%; Figure 3a) reduction between before and after periods. The probability that this percent change was >0 was high (pd = 0.96).

The BACI Contrast suggested that the difference in λ due to automated curtailment was −4.91 eagles killed per year on average (HDI = −11.27, 0.27; Figure 3b). The probability the BACI Contrast was negative was large (pd = 0.97), suggesting a high probability that λ decreased more at the treatment site than at the control site.

Finally, we plotted the yearly λ estimates per site (Figure 2b). During the before period, median λ was consistently similar to or lower at the control site than at the treatment site. It was only after the implementation of automated curtailment that median λ at the treatment site was lower than that of the control site.

4 | DISCUSSION

Science advances incrementally as techniques are refined and new data are collected. Despite the importance of confirmatory research to the scientific process, such studies are rarely published (Kelly, 2006; Nakagawa & Parker, 2015; Fraser et al., 2020). Here, we provide a confirmatory new analysis that improves statistical methodology, adds new data, confirms the original result, and increases the strength of our inference. Our preparation of this analysis was motivated by our desire to refine our work and by suggestions from colleagues about the timing of the before and after periods, the variation in turbine types, a focus on fatality rates, and use of standard BACI measures.

4.1 | Improvements to study design

We simplified interpretation of our results by removing data from the period during which automated curtailment units were being incrementally installed (Figure 1). Doing this ensured that we were comparing the time periods when automated curtailment was either completely absent or fully implemented. Interpretation of the current results is now more intuitive because there is no need to consider the effects of partial implementation of the treatment. Further, the staggered installation of automated curtailment units previously meant that the lengths of before and after periods were different at the two sites. This required us to adjust for turbine-days in the inter-site comparison—a procedure that complicated the interpretation of results. In the present analysis, although the before and after periods differ in length from each other, the durations are the same at each site and we can now intuitively and directly compare the changes between sites.

In our previous analysis, we examined deaths of eagles at two types of wind turbines—those manufactured by General Electric (GE) and by Siemens—while our control site only had GE turbines. Although we stand by this choice, there is sometimes concern in the research community that different turbine types may each cause unique fatality rates (TEK, personal observation; however, recent research may undermine this concern, e.g. Huso et al., 2021). As such, we understand that using data from two types of turbines might complicate interpretation and perhaps introduce unwanted variation. To accommodate this concern, in the present analysis we ignored the Siemens turbines and focused only on data from GE turbines. That the control and treatment sites both contain 66 turbines of identical manufacturer and model eliminates any questions introduced by comparison of different turbine types and numbers. These strict control conditions convey the same message as in the prior analysis—that automated curtailment appeared to lower the fatality rate of eagles at our treatment site.

The previous analysis focused on counts of dead eagles and therefore left open for interpretation the question of whether the decline in observed fatalities at the treatment site could have been the result of natural fluctuations that might have occurred in the absence of automated curtailment. Our revised analysis examines changes in the underlying rate of fatality (λ), instead of the yearly outcome of that rate (i.e. the number of eagles killed). This updated result confirms that the automated curtailment we evaluated probably reduced the number of eagles killed at GE wind turbines, both relative to the same turbines in the before period and relative to the control site during the after period.

Next, to improve our inference, we calculated the standard measure used to evaluate the effects of a treatment in a BACI study design (Chevalier et al., 2019). The measures we used in the past study—observed numbers of fatalities corrected by turbine-days and then converted to percentages—were less straightforward to interpret. The measure we present here—the BACI Contrast—is recognizable to the research community and represents a direct comparison of the rates (λ's) at which eagles were killed between before and after periods at each site.

Finally, our examination of yearly fatality rates demonstrates that the control site was consistently similar to or less deadly to eagles than the treatment site during the before period. After automated curtailment was implemented at the treatment site, the control site became the more deadly of the two sites (Figure 2b). This observation lessens the concern that our results are due to natural fluctuations in fatality rates, although it would be good to confirm this result with additional years of 'after' data.

4.2 | Inference and next steps

In this analysis, as in our previous one (McClure, Rolek, Dunn, et al., 2021), we demonstrate a reduction of eagle fatalities following implementation of automated curtailment. Before automated curtailment was implemented, the treatment site was consistently as or more deadly to eagles than the control site. After automated curtailment was implemented, the treatment site appeared safer to eagles than the control site. The median estimate we report here for the percent reduction in fatality rate due to automated curtailment (median = 85%; 11%, 100%) is similar to the estimate from our prior study suggesting an 82% (75%, 89%) reduction in number of fatalities (McClure, Rolek, Dunn, et al., 2021). The main difference between the numbers we report in the two studies is in the uncertainty associated with our estimates. The confidence intervals we presented in our original study were too precise because detection rates were high and because we calculated and compared an estimate of a count of eagles killed. There was therefore little uncertainty in the changes in the number of eagles killed at each site and during each time period. The estimate of the fatality rate (λ) is inherently less precise than the estimate of its outcome (the number of eagles killed in a given year) because the rate cannot be directly observed. The confidence in our median estimates is therefore lower in the current study than in the prior one, but the broad error estimates represent a more appropriate level of confidence and lead to stronger inference.

The BACI Contrast recommended by Chevalier et al. (2019) lends further insight into our results. Our analyses suggest that the annual fatality rate declined by nearly 5 eagles per year more at the treatment site than at the control site. This is consistent with the strongly negative value of the BACI Contrast, indicating that there was a greater decrease in fatality rate (λ) at the treatment site than the control site.

Revisiting our earlier analysis provided the opportunity to add data collected since publication, thus expanding the temporal scope of our analysis. By adding the 2020 data, we demonstrate that the fatality rate at the treatment site remained low for a full year after implementation of automated curtailment. Indeed, a single eagle was observed to have been killed by GE turbines at the treatment site in the calendar year of 2020, compared to six in 2017, the year before any automated curtailment measures were in place.

The analysis we performed here supports our earlier study (McClure, Rolek, Dunn, et al., 2021) by showing that fatality rates at the treatment site declined relative to the control site after the implementation of automated curtailment. Our study design assumes that the only condition varying systematically between the two sites and time periods is the implementation of automated curtailment. However, other potential causes must be considered. As with our previous study, changes in eagle distribution and behaviour, or in prey and carrion availability, could have induced differing fatality rates unrelated to curtailment regimes. We do not have data to test hypotheses that something other than curtailment caused the observed changes in the fatality rate, nor do we have any indication that there were other processes ongoing that could have caused the changes we observed. That the treatment site was consistently as or more deadly to eagles than the control site during the before period discounts the assertion that our results might be due to random fluctuations in fatality rates. Further, that the yearly fatality rates at the two sites appeared to change in concert during the before period (Figure 2b) suggests that our control site was appropriate for comparison to the treatment site.

Each curtailment reduces the amount of energy produced by a wind power facility. Indeed, the IdentiFlight system often mistakes other large birds for eagles (McClure et al., 2018) and thus there is potential for unwarranted curtailment. We do not have information regarding the rate of curtailments for non-eagles during our study. However, a previous study (McClure, Rolek, Braham, et al., 2021) revealed that only 29.5% of birds classified as eagles that flew within 150 m of a turbine actually entered the rotor-swept zone. Opportunity thus exists to reduce power losses by adjusting curtailment criteria (McClure, Rolek, Braham, et al., 2021).

There is therefore much more to do in identifying the role that automated curtailment can have in protecting wildlife, globally, from collisions with wind turbines. Few past studies were designed to allow a BACI comparison (Conkling et al., 2020), although this study design is preferable when evaluating mitigation efforts (Köppel et al., 2014). Although an important first step, our work regarding automated curtailment is limited to a single site, within a limited time frame and under particular settings. Inference from this study is especially hampered by the fact that we only examine a single year post implementation of automated curtailment. Efficacy of automated curtailment will thus likely be evaluated at other sites, with other species and over longer time periods. These tests will determine whether our results are representative of a broader pattern or a unique site- and species-specific characteristic. In particular, changes to the site-specific programming of the IdentiFlight system, especially in the code that determines when to curtail turbines, would have substantial implications, not only for fatality rates but also for the rate at which power production is impacted by curtailment. Further research might also explore methods to simultaneously minimize the fatality rate (λ) and the number of curtailments, so that automated curtailment can be implemented in support of sustainable wind energy.

ACKNOWLEDGEMENTS

We appreciate the advice and feedback from Matt Stuber, and many others who gave us constructive criticism on the earlier version of this manuscript. Funding for this work was provided by the MJ Murdock Charitable Trust and donors to The Peregrine Fund. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

AUTHOR CONTRIBUTIONS

Christopher McClure and Todd Katzner conceived the study. Christopher McClure conducted analysis and wrote initial draft. Luke Martinson oversaw field data collection. All authors assisted with analytical design and substantially edited drafts of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data are available from the Dryad digital repository https://doi.org/10.5061/dryad.wm37pvmqr (McClure et al. 2022).

PEER REVIEW

The peer review history for this article is available at: https://publons.com/publon/10.1002/2688-8319.12173.

ORCID

Christopher J. W. McClure https://orcid.org/0000-0003-1216-7425
Todd E. Katzner https://orcid.org/0000-0003-4503-8435

REFERENCES

Akaike, H. (1974). A new look at the statistical model identification. *IEEE Transactions on Automatic Control*, *19*(6), 716–723.

Allen, M., Poggiali, D., Whitaker, K., Marshall, T. R., & Kievit, R. A. (2019). Raincloud plots: A multi-platform tool for robust data visualization. *Wellcome Open Research*, *4*, 63.

Allison, T. D., Diffendorfer, J. E., Baerwald, E. F., Beston, J. A., Drake, D., Hale, A. M., Hein, C. D., Huso, M. M., Loss, S. R., Lovich, J. E., Strickland, M. D., Williams, K. A., & Winder, V. L. (2019). Impacts to wildlife of wind energy siting and operation in the United States. *Issues in Ecology*, *21*, 2–22.

Chevalier, M., Russell, J. C., & Knape, J. (2019). New measures for evaluation of environmental perturbations using Before-After-Control-Impact analyses. *Ecological Applications*, *29*, e01838.

Conkling, T. J., Loss, S. R., Diffendorfer, J. E., Duerr, A., & Katzner, T. E. (2020). Limitations, lack of standardization, and recommended best practices in studies of renewable energy effects on birds and bats. *Conservation Biology*, *35*, 64–76.

Dalthorp, D. H., Simonis, J., Madsen, L., Huso, M. M., Rabie, P., Mintz, J. M., Wolpert, R., Studyvin, J., & Korner-Nievergelt, F. (2018).

Generalized Mortality Estimator (GenEst) - R code & GUI: U.S. *Geological Survey Software Release*, v 1.4.4 .

Dalthorp, D., Huso, M., & Dail, D. (2017). *Evidence of absence (v2. 0) software user guide*. US Geological Survey. https://pubs.er.usgs.gov/publication/ds1055

Dalthorp, D., Simonis, J., Madsen, L., Huso, M., Rabie, P., Mintz, J., Wolpert, R., Studyvin, J., & Korner-Nievergelt, F. (2020). GenEst: Generalized mortality estimator. R package version 1.4.4.

Fraser, H., Barnett, A., Parker, T. H., & Fidler, F. (2020). The role of replication studies in ecology. *Ecology and Evolution*, *10*, 5197–5207.

Hurvich, C. M., & Tsai, C. L. (1989). Regression and time-series model selection in small sample sizes. *Biometrika*, *76*, 297–307.

Huso, M., Conkling, T., Dalthorp, D., Davis, M., Smith, H., Fesnock, A., & Katzner, T. (2021). Relative energy production determines effect of repowering on wildlife mortality at wind energy facilities. *Journal of Applied Ecology*, *58*, 1284–1290.

Kelly, C. D. (2006). Replicating empirical research in behavioral ecology: How and why it should be done but rarely ever is. *Quarterly Review of Biology*, *81*, 221–236.

Köppel, J., Dahmen, M., Helfrich, J., Schuster, E., & Bulling, L. (2014). Cautious but committed: Moving toward adaptive planning and operation strategies for renewable energy's wildlife implications. *Environmental Management*, *54*, 744–755.

Makowski, D., Ben-Shachar, M., & Lüdecke, D. (2019). bayestestR: Describing effects and their uncertainty, existence and significance within the Bayesian framework. *Journal of Open Source Software*, *4*, 1541.

May, R., Nygård, T., Falkdalen, U., Åström, J., Hamre, Ø., & Stokke, B. G. (2020). Paint it black: Efficacy of increased wind turbine rotor blade visibility to reduce avian fatalities. *Ecology and Evolution*, *10*, 8927–8935.

McClure, C. J. W., Martinson, L., & Allison, T. D. (2018). Automated monitoring for birds in flight: Proof of concept with eagles at a wind power facility. *Biological Conservation*, *224*, 26–33.

McClure, C. J. W., Rolek, B. W., Braham, M. A., Miller, T. A., Duerr, A. E., McCabe, J. D., Dunn, L., & Katzner, T. E. (2021). Eagles enter rotor-swept zones of wind turbines at rates that vary per turbine. *Ecology and Evolution*, *16*, 11267–11274.

McClure, C. J. W., Rolek, B. W., Dunn, L., McCabe, J. D., Martinson, L., & Katzner, T. (2021). Eagle fatalities are reduced by automated curtailment of wind turbines. *Journal of Applied Ecology*, *58*, 446–452.

McClure, C. J. W., Rolek, B. W., Dunn, L., McCabe, J. D., Martinson, L., & Katzner, T. (2022). Confirmation that eagle fatalities can be reduced by automated curtailment of wind turbines. *Dryad, Dataset*, https://doi.org/10.5061/dryad.wm37pvmqr

Nakagawa, S., & Parker, T. H. (2015). Replicating research in ecology and evolution: Feasibility, incentives, and the cost-benefit conundrum. *BMC Biology*, *13*, 1–6.

Simonis, J., Dalthorp, D. H., Huso, M. M., Mintz, J. M., Madsen, L., Rabie, P., & Studyvin, J. (2018). *GenEst user guide—Software for a generalized estimator of mortality* (No. 7-C19). U.S. Geological Survey.

R Development Core Team. (2018). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. AIC tables of models for searcher efficiency at Campbell Hill (control) and Top of the World (treatment) wind power facilities Wyoming, USA. We retained the models with the lowest AIC values for analysis. Estimates are from a before-after-control-impact design where wind turbines were never curtailed to prevent fatalities at the control site.

Table S2. AIC tables of carcass persistence at Campbell Hill (control) and Top of the World (treatment) wind power facilities in Wyoming, USA. We retained the models with the lowest AIC values for analysis. Estimates are from a before-after-control-impact design where wind turbines were never curtailed to prevent fatalities at the control site.

Table S3. Median and lower and upper bounds of the 95% highest density intervals of 10,000 bootstrap iterations of carcass detection probabilities at Campbell Hill (control) and Top of the World (treatment) wind power facilities Wyoming, USA. Estimates are from a before-after-control-impact design where wind turbines were never curtailed to prevent fatalities at the control site.

How to cite this article: McClure, C. J. W., Rolek, B. W., Dunn, L., McCabe, J. D., Martinson, L., & Katzner, T. E. (2022). Confirmation that eagle fatalities can be reduced by automated curtailment of wind turbines. *Ecological Solutions and Evidence*, *3*, e12173. https://doi.org/10.1002/2688-8319.12173