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Incidental eagle carcass detection can contribute to fatality estimation at operating wind energy facilities

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Abstract

Risk of birds colliding with wind turbines, especially protected species like bald eagle and golden eagle in the U.S., is a fundamental wildlife challenge the wind industry faces when developing and operating projects. The U.S. Fish and Wildlife Service requires wind energy facilities that obtain eagle take permits document permit compliance through fatality monitoring. If trained Operations and Maintenance (O&M) staff can reliably detect and report carcasses during their normal routines, and their detection probability can be estimated, then their 'incidental detections' could contribute substantially towards demonstrating permit compliance. Our primary objective was to quantify incidental detection of eagle carcasses by O&M staff under a variety of landscape contexts and environmental conditions throughout a single year. We used the incidental detection probabilities, along with raptor carcass persistence data and area adjustments, to calculate overall probability of incidental detection (i.e., incidental *g*). We used feathered decoys as eagle-carcass surrogates for monthly detection trials at 6 study sites throughout the U.S. We evaluated the primary drivers of incidental detection using logit regression models including season, viewshed complexity, and a derived variable called the "density quartile" as covariates. We used an Evidence of Absence-based approach to estimate the overall probability of incidental detection. The incidental detection probabilities ranged from 0.28 to 0.78 (mean = 0.48). Detection probabilities decreased as viewshed complexity increased and as distance from the turbine increased. The resulting overall probability of incidental detection ranged from 0.07 to 0.47 (mean = 0.31). The primary drivers of variability in incidental *g* were detection probability and the area adjustment. Results of our research show that O&M staff were effective at detecting trial carcasses incidentally. Incorporating incidental detection in eagle fatality monitoring efforts is a reliable means of improving estimates of a facility's direct impacts on eagles.

Introduction

Risk of birds colliding with wind turbines, especially sensitive or protected species, is a fundamental wildlife challenge the wind industry faces when developing and operating facilities [1].

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Bald eagles (*Haliaeetus leucocephalus*) and golden eagles (*Aquila chrysaetos*) are susceptible to collision with wind turbines [2–4] and are protected under federal law in the U.S. [5]. Wind energy companies that obtain eagle take permits (ETPs), per the revised eagle permitting rules [6], are required by the U.S. Fish and Wildlife Service (USFWS) to complete eagle fatality monitoring to document permit compliance. Some level of eagle fatality monitoring will remain a requirement for all ETPs issued under the recently proposed revisions to the eagle permitting rules [7]. Given a permit term up to 30-years and a need to assess take compliance in 5-year increments, monitoring will be long-term with potentially high cost implications.

Eagle fatality monitoring has traditionally been completed by third parties hired to conduct standardized transect searches; however, over half of all reported eagle fatalities at wind energy facilities from 1997 to 2012 were detected incidentally outside of these standardized searches (i.e., the fatalities were detected by a property owner or by facility employees during routine site operations [3]). Incidental detections likely occur because eagle carcasses are large, tend to be highly visible, and have long persistence times [8–11]. Operations and Maintenance (O&M) staff, while traveling access roads and performing their typical duties on a near daily basis, have a more consistent presence on site than a third party. Furthermore, because O&M staff are visiting all turbines on a regular basis, there is likely more comprehensive spatial coverage of a facility compared to third-party monitoring that has traditionally been limited to a subset of turbines, and maximizing spatial coverage is desirable when monitoring for rare events such as eagle fatalities [12]. If O&M staff are educated on the importance of being aware of and reporting of potential eagle fatalities and receive training to reliably detect and report carcasses found during their regular work schedule, eagle carcasses detected incidentally by O&M staff at some wind energy facilities could provide valuable information for compliance monitoring required by ETPs.

Accurate fatality estimates based on monitoring (whether standardized or incidental) require an adjustment for the overall probability of detection [13, 14]. Although a number of fatality estimation models exist, Evidence of Absence (EoA; [15]) is a tool often used to estimate eagle fatality rates to determine permit compliance. EoA is specifically designed for fatality estimation in the context of "rare events" (i.e., 0 or very few carcasses are expected to be found during each search), which is the expectation for eagle fatalities at most wind energy facilities. EoA requires that an estimate of the overall probability of detecting an eagle carcass (g) is calculated for the period of interest, which incorporates estimate uncertainty and results in an estimate of eagle fatalities that may be higher than the number of observed eagle carcasses. Lower g results in higher uncertainty in the fatality estimate; conversely, a higher g will result in a more precise fatality estimate that is closer (or equal to) the observed count of carcasses (including 0).

Typical standardized fatality monitoring studies implemented by a third party have used EoA to estimate an overall g and a fatality estimate for eagles. Approaches to incorporate incidental detections in EoA have been explored in theory [16]; however, the contribution of incidental detection in practice has been overlooked to date, and an incidental g has not yet been quantified for wind energy facilities (herein, we use incidental detection and incidental g interchangeably). In several ETPs recently issued by the USFWS, an estimate of g has been required in all years covered under an ETP [17–20]. Quantifying incidental detection and including its contribution in fatality monitoring plans will allow permittees to increase overall g for the permit term, develop a more accurate estimate of impacts to eagles, and provide the most robust means to demonstrate compliance.

Using incidental detection in eagle take estimation requires the information necessary to calculate g: bias correction factors include carcass *detection probability* (what is typically referred to as "searcher efficiency" in post-construction fatality monitoring), *carcass persistence*

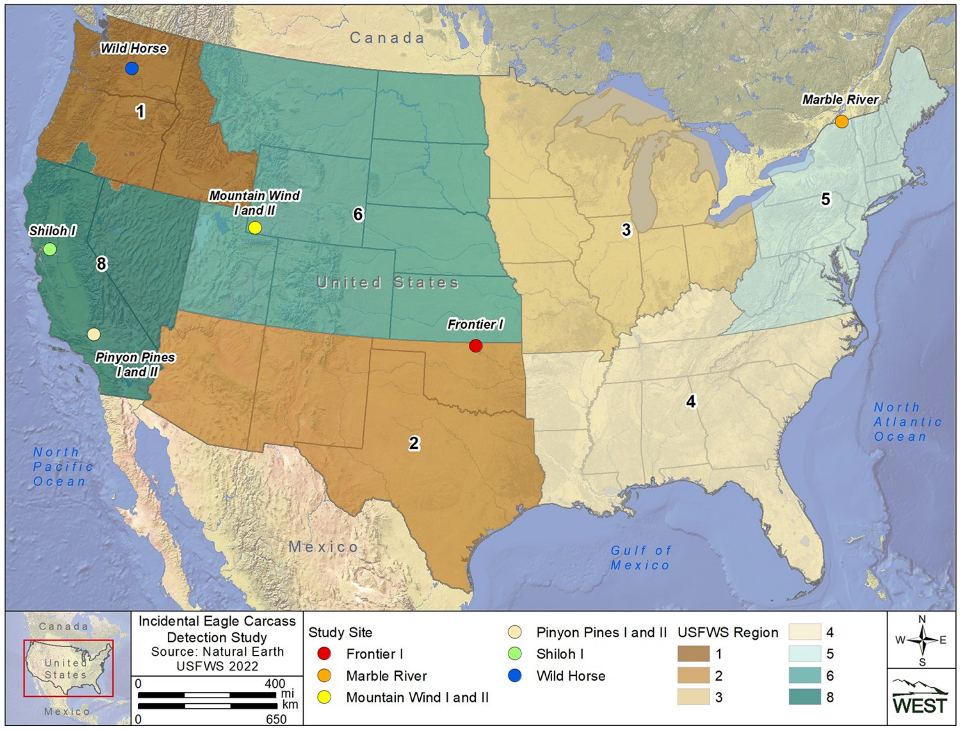

Fig 1. Study site locations included in the incidental eagle carcass detection study conducted from June 27, 2021, through July 14, 2022.

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(the probability of carcasses persisting between detection opportunities), and an *area adjustment* (the proportion of carcasses present within the searched areas, and the proportion of turbines where detection was possible [i.e., sampled turbines]; referred to elsewhere as density-weighted proportion, or DWP [13, 14]). The primary objective of this study was to quantify incidental detection of an eagle carcass surrogate by O&M staff during their normal maintenance activities under a variety of landscape contexts and environmental conditions throughout a single year. Our secondary objective was to use the incidental detection probabilities from each site, along with area adjustments and relevant raptor carcass persistence data, to calculate incidental *g*'s that could contribute to an improved understanding of a facility's direct impacts on eagles.

Study areas

Five different USFWS Regions were selected (Regions 1, 2, 5, 6, and 8; Fig 1 [21–23]) for field trials to help capture a range of typical wind energy facility characteristics across the U.S. (Fig 2) and determine the variability of incidental eagle carcass detection across wind energy facilities. Geographic location, facility size (number of turbines), ground conditions, topography, and O&M staff activity on site (i.e., turbine visitation schedules) were all considered when evaluating candidate wind energy facilities for inclusion in this study. Field trials were conducted at 6 different wind energy facilities (study site[s]). General characteristics of each study site are provided in Table 1.

Methods

To meet our first objective, we mapped viewshed complexity classes around turbines, and conducted incidental detection trials using eagle carcass surrogates placed at the 6 Study Sites

Fig 2. Examples of variable land cover types present at the wind energy facilities included in this study. The study sites shown in the photographs are: a) Shiloh I, b) Frontier I, c) Pinyon Pines I and II, d) Wild Horse, e) Mountain Wind I and II, and f) Marble River. Decoy placements are visible in photographs a, b, d, and f.

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(Table 1, Fig 2) to estimate and directly compare incidental detection probabilities in a variety of landscape contexts. We used these incidental detection probabilities to explore spatial (e.g., distribution of viewshed complexity classes around turbines) and temporal (e.g., seasons) patterns and identify the primary drivers of incidental detection at our study sites. To meet our second objective, we combined these detection probabilities with relevant carcass persistence data and area adjustments to calculate incidental *g*'s for eagles. We then used these incidental *g*'s in a rare-event estimation context to evaluate the importance of including incidental detection when quantifying eagle fatalities.

Viewshed complexity mapping

We expected detection probability to be influenced by viewshed complexity (i.e., the height/density of vegetation and variation in topography) that could conceal carcasses from view within the searchable area at each turbine. Therefore, prior to the field trials, we mapped the viewshed complexity classes within the search area, defined as a 100-m radius circle centered on every turbine, at all 6 study sites. We categorized viewshed complexity as low, moderate, or high complexity based on ground cover conditions shown in Table 2. We also characterized areas as unviewable/unsearchable when visibility out to 100 m was limited by variation in terrain, mature crops, or forest. Areas categorized as unviewable/unsearchable were not visible by O&M staff conducting regular maintenance duties, such as when traveling in a vehicle to a

Table 1. Study site descriptions for the incidental eagle carcass detection study[a].

Study Site	USFWS Region	Nameplate Megawatt Capacity for the Site	Total Number of Turbines	Turbine Specifications (MW Rating, Hub Height, Tip Height)[b]	Start of Commercial Operations	USEPA Ecoregion (Level IV)	Primary Land Use(s)	Primary Land Cover (s)	Turbine Visitation Schedule
Frontier I	2	200	61	3.3 MW, 87 m, 148.7 m	December 2016	Prairie Tableland [24]	Cropland	Cropland	Monthly inspections
Marble River	5	215	70	3.0 MW, 93 m, 148 m	October 2012	Ontario Lowlands [25]	Cropland and livestock grazing	Forest and agriculture	Monthly inspections, unless inaccessible due to snow cover
Mountain Wind I and II	6	141	67	2.1 MW, 80 m, 124 m	September 2010	Rolling Sagebrush Steppe [26]	Livestock grazing	Sagebrush-steppe and grassland	Monthly inspections, unless inaccessible due to snow cover
Pinyon Pines I and II	8	300	100	3.0 MW, 80 m, 125 m	December 2012	Western Mojave Basin [27]	Livestock grazing	Desert shrub	Routine inspections varied due to weather conditions; approximately monthly
Shiloh I	8	150	100	1.5 MW, 80 m (76 turbines) and 65 m (24 turbines), 117 m	April 2006	Suisun Terraces and Low Hills [28]	Livestock grazing and cropland	Grassland and cropland	Monthly inspections
Wild Horse	1	273	127	1.8 MW (127 turbines) and 2.0 MW (22 turbines), 67 m, 107 m	December 2006	Yakima Folds and Okanogan Drift Hills [29]	Livestock grazing	Shrub-steppe and grassland	Monthly inspections

Study conducted at the study sites from June 27, 2021, through July 14, 2022.

[a] Abbreviations: MW = megawatts, USFWS = U.S. Fish and Wildlife Service, USEPA = U.S. Environmental Protection Agency

[b] Data in this column include the total megawatts (MW), the number of turbines (if turbines with differing MW capacity or heights were present), and the hub height and tip height, which are presented in m above ground level.

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turbine or when they were standing near turbine bases or edges of turbine pads. Mapped viewshed complexity classes were digitized in ArcGIS [30]. Based on the viewshed mapping performed at the beginning of our study and the ground cover conditions present within the search areas, we inferred predominant viewshed complexity classes by season at each study site. For example, we assumed cropland areas typically progressed from low to moderate to unviewable/unsearchable across the crop-growing cycle.

We also classified viewshed complexity for each decoy placed during our detection trials. Classifications were made based on the same parameters described above but limited to ground cover within a 5-m radius around each placement. By determining real-time viewshed

Table 2. Viewshed complexity classifications.

	Average Vegetation Height in Non-Bare Ground Areas				
Percent Bare Ground	**<15 cm**	**16–30 cm**	**31–45 cm**	**> 46 cm**	**Rocky**
> 90%	Low	Low	Low	Low	Moderate
26–89%	Low	Moderate	Moderate	Moderate	Moderate
1–25%	Low	Moderate	High	High	High
0%	Low	Moderate	High	High	High

Classifications were based on percent bare ground and vegetation height within the 100-m radius search areas centered on wind turbine towers during detection trials conducted at the study sites from June 27, 2021, through July 14, 2022.

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complexities associated with each opportunity for detection, we were able to evaluate the effects of viewshed complexity on detection probabilities.

Field methods for incidental detection trials

We used Turkey Skinz™ (A-Way Hunting Products, Beaverton, Michigan) feathered turkey (*Meleagris gallopavo*) decoys as eagle carcass surrogates for all detection trials. Decoys were used to approximate the size and color (and, therefore, detectability) of an eagle carcass ([10, 31], Fig 3), and were also a practical choice to obtain adequate sample size and ensure decoys were still in place when the opportunity for detection occurred. Eagle carcasses and parts are protected by federal law and are prioritized for Native American religious purposes, so obtaining authorization to use eagle carcasses for site-specific detection trials would have been unlikely even if enough carcasses were available to meet our sample size requirements. Using decoys in detection trials also does not require state or federal permits, which are needed if actual raptor carcasses are used; these permits can be difficult to obtain, particularly in a timely fashion. Lastly, decoys do not introduce collision risk to aerial scavengers that may be attracted to real carcasses placed in the hazardous area near turbine bases.

Decoy placements were assigned a random distance and bearing from the base of randomly selected turbines throughout the study period. Decoy placement distances were randomized from a distribution of raptor fall distances derived from a meta-analysis [10], truncated to 100 m from the turbine base, which captures approximately 94.5% of expected raptor fatalities for the turbine sizes at our study sites. Thus, the density of decoy placements increased from 0 to 40 m from the turbine base and then decreased out to 100 m [10]. Placement bearing-from-turbine was chosen from a uniform distribution between 0 and 360 degrees. To the extent possible, placements were stratified across the mapped viewshed complexity categories (low, moderate, high). No decoy was placed in an unviewable/unsearchable area.

We deployed 11–16 decoys per study site per month (mean = 15.4, standard deviation = 2.7), for approximately 48 uniquely tagged decoys at each study site per quarter. All decoys were placed on a single day each month unless site conditions or other field delays required placements spanning 2 days. Western EcoSystems Technology, Inc. (WEST), personnel placed the decoys without the direct knowledge of the O&M staff, and most placements occurred on weekends or after hours when O&M staff were not present.

Decoys were left in place for 1 month or until they were detected, whichever was sooner. One month was chosen as our trial length, as this timeframe aligned with a common visitation schedule for O&M staff making periodic visits to perform maintenance checks all study site turbines. O&M staff do not typically record their movements or track their visitation schedule to study site turbines; as such, we conservatively assumed each decoy had at least 1 opportunity for detection during each round of placements. Prior to field trials, O&M staff were briefed on the objectives of the study and instructed on detection and documentation protocols but were directed to not otherwise deviate from their typical maintenance routines. When a decoy was detected by O&M staff, the decoy was immediately collected from the field, deposited at the O&M building, and reported by O&M staff using a simple decoy detection form. O&M staff were asked to record the date, nearest turbine, their activity when the detection was made, and the decoy tag identification.

Seasonal adjustments to deployment schedules were needed at several study sites. During the winter months, roads were not cleared of snow at Marble River, Mountain Wind I and II, and Wild Horse, and on-site travel was limited to as-needed maintenance visits. Furthermore, frequent snowfall was anticipated to obscure decoy (or carcass) presence on the landscape at those 3 study sites. Opportunities for decoy detection were expected to be minimal under

Fig 3. A side-by-side comparison of the feathered turkey decoys used in our incidental detection trials and actual eagle carcasses found at wind energy facilities. The photographs are: a) feathered turkey decoy, b) bald eagle carcass, and c) golden eagle carcass.

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these conditions, so no decoys were placed, and detection was assumed to be 0 from December 2021 –March 2022 at Marble River, from January–March 2022 at Mountain Wind I and II, and from December 2021 –January 2022 at Wild Horse. In 2 cases, winter weather conditions also resulted in abbreviated trials. At Mountain Wind I and II, decoys placed on November 30,

Table 3. Season dates for the incidental eagle carcass detection study.

Site	Season Dates			
	Spring	Summer	Fall	Winter
Frontier I	March 16 –June 15	June 16 –August 31	September 1 –December 15	December 16 –March 15
Marble River	April 1 –June 25	June 26 –August 30	August 31 –November 30	December 1 –March 31
Mountain Wind I and II	April 1 –June 30	July 1 –September 20	September 21 –November 30	December 1 –March 31
Pinyon Pines I and II	March 1 –May 31	June 1 –August 31	September 1 –November 30	December 1 –February 28
Shiloh I	April 1 –June 30	July 1 –September 30	October 1 –December 31	January 1 –March 31
Wild Horse	March 1 –May 31	June 1 –August 31	September 1 –November 30	December 1 –February 28

Dates for the incidental eagle carcass detection study at the 6 study sites from June 27, 2021, to July 14, 2022.

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2021, were retrieved on December 14, 2021, ahead of a predicted snowstorm, approximately 2 weeks short of the standard trial length. At Wild Horse, decoys placed on November 30, 2021, became completely covered in snow after an unexpected snowstorm on December 22, 2022. Despite the shortened trial length, the number of decoys detected by O&M staff before being covered by snow was consistent with the number of decoys detected in previous months at these sites. Thus, we assumed the decoys were placed ahead of all or most O&M visits to turbines that month and these placements should be included in analysis despite the abbreviated trial period potentially limiting additional opportunities for detection.

We also anticipated decoy detection would be negligible in cropland areas when crop heights exceeded the size of the carcass. Therefore, no deployments were made in cropland areas during the summer growing season. All areas temporarily or permanently excluded from the monthly trial schedule were accounted for in the area adjustment component when calculating the overall probabilities of incidental detection (see Area adjustment section, below). Specifically, 24 turbines at Frontier I and 41 turbines at Shiloh I were treated as unsearchable cropland during the summer season. We considered all major changes in land cover due to snowfall or agricultural activity (e.g., harvest time) when determining season dates for each study site (Table 3), as these changes were expected to impact detection probability. We attempted to make seasons equal in length to the greatest extent practicable.

Other conditions at some study sites made decoy placements at some turbines infeasible or inappropriate for the objectives of our study. For example, Marble River and Frontier I had landowners who did not permit decoy placements on their land during the entire study. This restriction excluded 12 turbines at Marble River and 1 turbine at Frontier I. An additional 6 turbines at Shiloh I did not receive placements during 1 month in spring because the property was not accessible. Finally, 10 turbines at Shiloh I were subject to dedicated wildlife monitoring in the spring and fall, so no decoys were placed at these turbines to avoid biasing the results with detections from standardized searches. Nonetheless, turbines at which decoys could not be placed were considered searchable and assumed to be similar to other turbines at the same study site with respect to viewshed complexity and the visitation schedule by O&M staff.

Analysis methods

Incidental detection trials. We summarized incidental detection data by study site, viewshed complexity class, and season using only decoys determined to be available for detection. Decoys were considered available unless they were not found by O&M staff and could not be recovered by the trial administrator following the month-long trial period. Decoys detected by O&M staff during the month-long trial period after placement were considered "found"; any decoys collected after the month-long trial period were treated as "available and not found."

We also summarized the available self-reported detection data from O&M staff to determine general patterns in the activities being performed when detections occurred. Since data on which O&M activity contributed to detections were not reported consistently at each site throughout the entire year, we did not attempt to incorporate activity data into modeling the drivers of incidental detection.

We used the incidental detection trial data in 2 ways to accomplish different goals. The first use of incidental detection trial data was exploring spatial and temporal patterns across the 6 study sites, with the goal of providing inference about the drivers of detection. The second use of the incidental detection trial data was to calculate site-specific incidental *g*'s in the manner expected for a single site evaluating compliance with permit conditions. The second application of incidental detection trials is described in more detail below (see Calculating the overall probability of incidental detection [incidental *g*]). All analyses were conducted in the program R [32].

To explore potential drivers (i.e., covariates) of incidental detection, trial data were used to fit generalized linear mixed-effects models (GLMM) as implemented in the lme4 R package [33]. We used a binomial error distribution and included a random effect for site in each potential model to account for site to site variation not captured by fixed effects and allow the results to better generalize to other wind energy facilities. Fixed effects included in model selection were season, viewshed complexity, and a derived variable called the "density quartile". The density quartile provides a simplified way to associate decoys with their proximity to a turbine by creating distance bins that align with the expected density of raptor carcasses on the landscape (near: 0–33 m; near-mid: 34–45 m; far-mid: 46–61 m; and far: more than 61 m from turbine base; using carcass distribution in Hallingstad et al. [10]). For example, the first density quartile "near" is where we would expect the first 25% of large raptor fatalities to fall relative to a turbine. We fit all possible combinations of fixed effects and 2-way interactions between fixed effects, and a random effect for study site. We used an information theoretic approach known as AICc, or sample-size corrected Akaike Information Criterion [34] to compare candidate GLMMs. We considered the best supported model or models as those within 2 AICc of the model with the lowest AICc value. If there were multiple models with the same AICc value (i.e., models with different parameterizations of the same underlying model), we retained only one model for interpretation and inclusion in the model selection table. We generated 90% confidence intervals for model predictions using a parametric bootstrapping approach in the merTools R package [35].

Carcass persistence. Estimating the average probability of persistence is necessary to calculate *g* using EoA. When estimating eagle or other large raptor (i.e., raptors with a minimum 30-cm wing chord and 300-g mass) fatality rates, raptor persistence data should be used whenever possible; game birds (e.g., mallards [*Anas platyrhynchos*], ring-necked pheasants [*Phasianus colchicus*]) consistently have shorter persistence times than large raptor carcasses (e.g., red-tailed hawks [*Buteo jamaicensis*], great horned owls [*Bubo virginianus*]), which would result in a lower probability of persistence and an inflated fatality estimate [11]. However, site-specific raptor persistence data were not available for 4 of our 6 study sites. For Wild Horse, we used existing raptor persistence data collected on 58 large raptor carcasses placed between May 2016 and September 2020. For Shiloh I, we used 35 large raptor carcasses placed at adjacent facilities in the Montezuma Hills Wind Resource Area (S1 Appendix) between March 2012 and October 2013. For the remaining 4 study sites, we used large raptor persistence data from several other wind energy facilities that were comparable in location and/or site characteristics [11]. Analysis methods used to estimate the average probability of persistence are provided in S1 Appendix.

Area adjustment. The area adjustment component of g accounts for the amount of area within the nominal search region (in this case, 100-m radius search areas centered on each turbine) and the expected occurrence, or density, of carcasses on the landscape. The density-weighted area adjustment was estimated as the product of the proportion of viewable area around each turbine and a carcass-density distribution. The carcass-density distribution predicts the likelihood a carcass falls a given distance from the turbine base. At the study sites with restricted search areas (due to snowfall in winter and croplands at peak growing season), the amount of viewable area and/or proportion of searchable turbines were reduced based on the length of time carcass detection was not feasible.

The raptor carcass-density distribution from Hallingstad et al. [10] was used to calculate the searched area adjustment in this study. The density distribution developed in Hallingstad et al. [10] is based on a meta-analysis of raptor spatial data from multiple wind energy facilities with varying turbine designs and wind regimes.

Calculating the overall probability of incidental detection (incidental *g*). Estimating g depends on the carcass detection probability (i.e., the proportion of available decoys/carcasses found, and the factor by which detection probability decreases on subsequent searches [k]), carcass persistence (the probability of carcasses persisting between detection opportunities), and an area adjustment (the proportion of carcasses present within the searched areas, and the proportion of turbines where detection was possible [i.e., searched turbines]).

We used the EoA [15] modeling framework to estimate the incidental g at each study site resulting from detection of decoys by O&M staff during the study period, the raptor persistence data most appropriate for each site, and the area adjustment information. The estimated overall probability of a carcass being both available and incidentally detected (i.e., incidental g) can be approximated as

$$g \approx p{*}r{*}a, \tag{1}$$

where p is average detection probability (adjusted by the detection reduction factor [k] to account for multiple search opportunities, as described in greater detail below), r is the average probability of carcass persistence between detection opportunities, and a is the area adjustment. EoA allows g to be calculated for any strata or "class" (e.g., season within a site) using the Single Class Module, and then to combine g across all strata via the Multiple Class Module [15]. For each site, incidental detection trial effort and results could vary by season (based on changes in viewshed complexity over the course of a year), raptor persistence models could have seasonal covariates, and the area adjustment could vary based on changes in viewable area (e.g., due to crop cycles or winter access limitations). Thus, we used the Single Class Module to calculate incidental g by season. We did not additionally stratify by viewshed complexity class (or density quartile) because incidental detection trials were placed at random distances from turbines based on the expected fall distribution of raptors [10] at each study site, and therefore the results of those trials would be representative of the viewshed complexity distribution unique to each study site. Finally, based on known turbine maintenance visitation schedules, search interval was assumed to be 30 days (although many turbines would be visited [i.e., "searched"] more frequently during an average 30-day period) for the purposes of estimating persistence probabilities (i.e., the r component of incidental g).

Although the decoys placed in field trials were not designed to be present through multiple monthly visits by O&M staff, we considered the possibility that a real eagle carcass that goes undetected during 1 search might remain available for detection on subsequent searches–i.e., the influence of the detection reduction factor, or k. A carcass missed at least once likely has a lower detectability than a carcass that was not missed, possibly because the missed carcass was in a less exposed location or became less conspicuous between searches (e.g., due to decomposition). This required parameter in EoA can range from 0 to 1, where *k* equal to 0 implies a carcass missed on the first search opportunity would never be found on subsequent searches. A *k* of 1 implies detection probability remained constant no matter how many times a carcass was missed. Estimating *k* is difficult because it requires the placement and tracking of many real carcasses through multiple search rounds. We did not estimate *k* for our analysis, but rather assumed a value of 0.67 since it is currently the only published estimate of *k* and consistent with a previous study of fatality monitoring for eagles and large raptors [10, 36].

To calculate incidental *g* across the entire year for each site, we also considered a temporal component to eagle risk (this parameter, temporal coverage, is also required in the EoA modeling framework). Eagle use in some regions of the U.S. can vary throughout the annual cycle, limiting the risk of collision (and, therefore, the potential for an eagle fatality to occur) to certain seasons. However, we did not have access to data sufficient to quantify eagle use at each study site, and evaluating variability in collision risk throughout the year was beyond the scope of our study. Lacking more specific information, temporal risk was treated as uniform across the study period at each site. Consequently, the season-specific incidental *g* estimates calculated using the Single Class Module were combined using uniform weights (i.e., 0.25 in each season) in the Multiple Class Module. All estimates of incidental *g* and eagle fatality statistics were calculated using the EoA R package (version 2.0.7), using the Single Class Module and Multiple Class Module of EoA [15].

Results

Viewshed complexity mapping

The predominant viewshed complexity classes varied by season at 3 of our 6 study sites (S1 Table). For cropland areas, the percentage of high-complexity search area fluctuated as cropland visibility varied on a seasonal basis. For example, cropland viewshed complexity at Frontier I was predominately low during the fall and winter, but cycled through moderate, high, and unviewable/unsearchable in the spring and summer. To a lesser extent, viewshed classification cycling occurred over the course of the growing seasons at Marble River and Shiloh I; however, the 100-m radius search areas at Marble River were predominantly unviewable/unsearchable throughout the year due to extensive forest habitat. Viewshed complexity within other land cover types remained relatively consistent from season to season. Reduced on-site travel during the winter season due to large amounts of snowfall is another mechanism through which viewshed complexity varied seasonally (S1 Table).

Incidental detection trials by study site

Over the 12-month study, we placed 996 decoys in the field (Table 4). Of the 996 decoy placements, 918 were confirmed as available for detection (either detected or collected at the end of the 30-day trial) and 444 of available decoys were detected by O&M staff (48%; Table 4); 78 decoy placements were unavailable for detection due to theft, agricultural activities, or undetermined means of removal. The detection probabilities ranged from 0.28 (Wild Horse) to 0.78 (Marble River; Table 4).

Variation in incidental detection at the study sites was driven primarily by variation in viewshed complexity. Decoy detection in high viewshed complexity ranged from no detection (0 out of 8 placements detected) at Marble River and Wild Horse (0 out of 6 placements detected) to 0.31 at Frontier I (8 out of 26 placements detected; S2 Table). In contrast, detection in low viewshed complexity ranged from 0.31 at Wild Horse (39 out of 126 placements detected) to 0.89 at Marble River (50 out of 56 placements detected), while detection in

Table 4. Incidental detection trial results by study site.

Study Site	Decoys Placed	Decoys Available	Decoys Found	Average Detection Probability (Decoys Found / Decoys Available)	Monthly Trials
Frontier I	177	140	63	0.45	12
Marble River	116	86	67	0.78	7
Mountain Wind I and II	144	144	91	0.63	8
Pinyon Pines I and II	192	188	59	0.31	12
Shiloh I	191	186	115	0.62	12
Wild Horse	176	174	49	0.28	11
Overall	**996**	**918**	**444**	**0.48**	**57**

Trial results for field studies during detection trials conducted at the study sites from June 27, 2021, through July 14, 2022.

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moderate viewshed complexity ranged from 0.09 at Frontier I (2 out of 22 placements detected) to 0.77 at Marble River (17 out of 22 placements detected; S2 Table).

Detection probability (decoys found divided by decoys available) also varied by season across study sites, with the greatest range in fall (0.16–0.94) and smallest range in winter (0–0.51; S3 Table). Detection probabilities at Frontier I and Shiloh I were lowest in spring (0.24 and 0.36, respectively). Detection probabilities at Marble River and Mountain Wind I and II were lowest in winter (0), as no trials were placed when snowfall limited on-site travel and would have obscured decoy placements. Detection at Frontier I was highest in winter (0.51), whereas at Shiloh I detection was highest in summer (0.86), and Marble River had the highest detection in fall (0.94). At Wild Horse and Pinyon Pines I and II, seasonal detection probabilities were less variable than at our other study sites (0.16–0.40 and 0.21–0.44, respectively; S3 Table).

The activity being performed when a decoy detection occurred was recorded for 307 out of the 444 detections (69%, S4 Table). Of these, most detections occurred while O&M staff were at turbines conducting routine inspections (106 detections; 35%), followed closely by detections made while driving (96 detections; 31%) and while performing turbine maintenance (91 detections; 30%; S4 Table). A small number of detections were made while performing other activities on-site, such as land management (e.g., weed control, mowing) or surveying (14 detections; 5%; S4 Table).

Modeling drivers of incidental detection. The best-supported model of incidental detection probability had an AICc value of 998.74, which was also the lowest AICc among candidate models (S5 Table) and included a fixed effect for density quartile, a fixed interaction between season and viewshed complexity, and a random intercept for site (S5 Table). For reference, we provide the parameter estimates for the best supported model (Table 5). There was a consistent pattern in the parameter estimates where the magnitude of the season-viewshed complexity interaction term was greatest when viewshed complexity was low, and decreased for medium and high viewshed complexity; in contrast, the influence of season on the interaction terms was generally smaller when comparing different interaction terms at the same viewshed complexity level (Table 5, Fig 4). The magnitude of the random effect for site was 0.89, slightly larger than the standard error for the overall intercept term (0.82; Table 5). Of the 16 model parameters, all were significant at the 0.05 significance level at a minimum, and 10 parameters were significant at a less than 0.001 significance level.

Estimates from the best supported model of incidental detection probability varied from 0.01 ([90% confidence interval (CI) 0–0.05]; far distance quartile in high viewshed complexity, spring) to 0.81 ([90% CI 0.67–0.90]; near distance quartile in low viewshed complexity, spring;

Table 5. Parameter estimates for the best-supported (AICc) GLMM of incidental detection probability.

Fixed Effects	Estimate	Standard Error	z Statistic	p-value
(Intercept)	-2.94	0.82	-3.57	<0.001
Density Quartile–near-mid	-0.52	0.21	-2.48	0.0132
Density Quartile–far-mid	-1.02	0.22	-4.72	<0.001
Density Quartile–far	-1.36	0.25	-5.34	<0.001
Season summer:Viewshed Complexity low	4.32	0.76	5.69	<0.001
Season fall:Viewshed Complexity low	4.29	0.76	5.67	<0.001
Season winter:Viewshed Complexity low	4.16	0.77	5.38	<0.001
Season spring:Viewshed Complexity low	4.40	0.77	5.74	<0.001
Season summer:Viewshed Complexity medium	3.71	0.79	4.67	<0.001
Season fall:Viewshed Complexity medium	2.70	0.79	3.40	<0.001
Season winter:Viewshed Complexity medium	2.32	0.85	2.74	0.0062
Season spring:Viewshed Complexity medium	2.77	0.77	3.59	<0.001
Season summer:Viewshed Complexity high	1.85	0.94	1.97	0.0494
Season fall:Viewshed Complexity high	2.52	0.99	2.55	0.0109
Season winter:Viewshed Complexity high	2.24	0.87	2.57	0.0103
Random Effects		Standard Error		
Site (intercept)		0.89		

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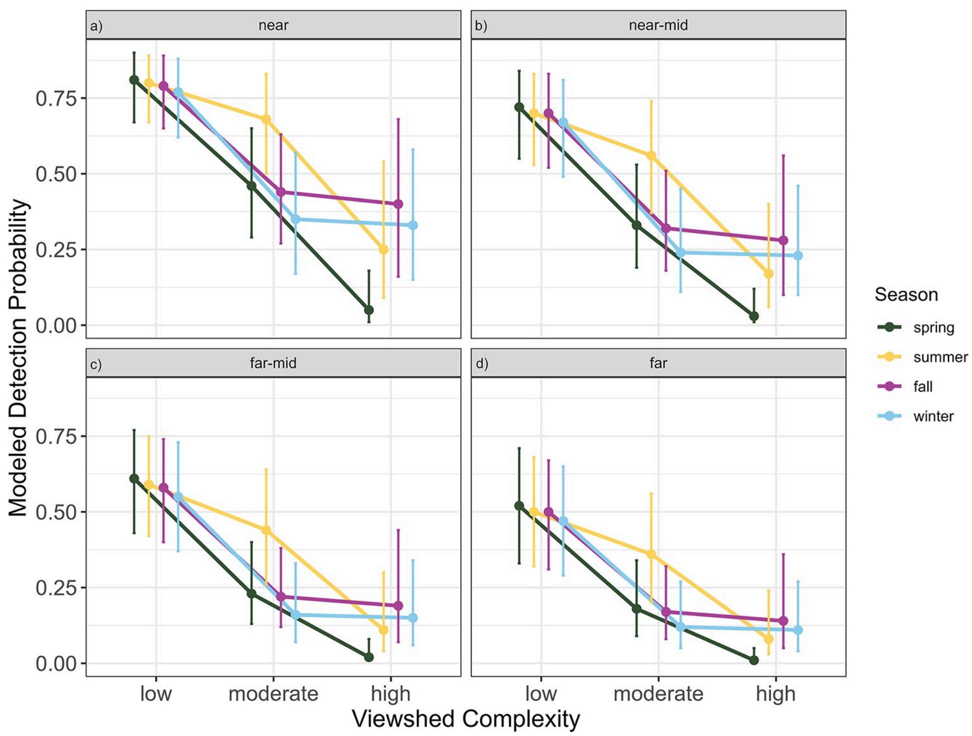

Fig 4. Interaction plot of viewshed complexity and season on incidental detection probability, separated by density quartile, with 90% confidence intervals. Modeled density quartiles are for the categories: a) near, b) near-mid, c) far-mid, and d) far. Estimates within each level of viewshed complexity are jittered to facilitate comparison of estimates across seasons. In all density quartiles, detection probability was highest within low viewshed complexity areas in all seasons. In summer, detection probability was higher in moderate viewshed complexity areas within all density quartiles compared to other seasons. In spring, detection probability was lower in high viewshed complexity within all density quartiles compared to other seasons.

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Fig 4). However, differences in incidental detection probability were driven by viewshed complexity and distance quartile more than season, consistent with the comparison of fixed effects, above. The average of point estimates in low, moderate, and high viewshed complexity were 0.64, 0.33, and 0.16, respectively, and the average of point estimates at the near, near-mid, far-mid, and far density quartiles were 0.51, 0.41, 0.32, and 0.26, respectively. Conversely, the average of point estimates for spring, summer, fall, and winter were 0.33, 0.44, 0.39, and 0.35, respectively. Moreover, the model describes a pattern of decreasing incidental detection probability as density quartile transitions form near to far within each viewshed complexity class and decreasing detection probability within each density quartile as viewshed complexity increases.

Carcass persistence

Comprehensive results from our average probability of persistence analyses are provided in S1 Appendix). Median raptor persistence was typically in excess of the 30-day search interval assumed for O&M staff visitation to turbines, ranging from 19.46 days at the study site with mostly forest land cover (Marble River, informed by Arkwright Summit Wind Farm [Arkwright]) to 170.12 days at the study site with mostly cropland (Shiloh I and Frontier I, informed by Hale Wind Farm). The average probability of persistence, which is a component of *g*, was also high relative to a 30-day search interval, at or exceeding 0.70 in all but 1 case (0.61; Marble River, informed by Arkwright; S1 Appendix).

Area adjustment and proportion of turbines visited

The amount of viewable area at turbines searched (i.e., those we assumed could be visited by O&M staff) for each study site varied by season, with the exception of Pinyon Pines I and II and Mountain Wind I and II, where effectively all areas within 100 m of a turbine were considered viewable in all seasons. Viewable area ranged from 0.183 (Marble River, summer) to 0.999 (Pinyon Pines I and II, all seasons studied; Table 6). Viewable area was lowest at study sites with cropland, particularly during the growing season (summer for our study sites), and at the study site with forest habitat (Marble River). The proportion of viewable area during the non-growing season varied at each of the study sites, but not consistently. Viewable areas during the non-growing seasons at Marble River and Shiloh I were 18% and 13% higher than during the growing season, respectively, while viewable area during the non-growing season at Frontier I was 188% higher. Accounting for the predicted density of raptor fatalities relative to distance from turbine, the density-weighted area adjustment followed the same pattern as proportion of viewable area, ranging from 0.301 (Marble River, summer) to 0.939 (Pinyon Pines I and II, all seasons studied). In some cases, the density-weighted area adjustment was greater than the proportion of viewable area (e.g., Marble River, all seasons; Table 6) because viewable areas were generally at distances from the turbine base that aligned with the highest density of predicted raptor fatalities from the distribution model in Hallingstad et al. [10]. Finally, the proportion of turbines we assumed to have been searched by O&M staff during each season was generally 1.0 (i.e., all turbines visited), with seasonal exceptions for turbines located in areas dominated by agriculture (summer) or where access was precluded by snowfall (winter; Table 6). These subsets of turbines were considered to have effectively no searchable area while conditions prevented detection.

Overall probability of incidental detection (Incidental *g*)

The resulting incidental *g* for the 12-month period for our study sites ranged from 0.07 (Marble River) to 0.47 (Mountain Wind I and II; Table 7). There was variability in incidental *g* by

Table 6. Area adjustment for unviewable/unsearchable areas and proportion of viewable area.

Study Sites	Season	Predominant Viewshed Within Viewable Area at Searched Turbines[a,b]	Proportion of Viewable Area at Searched Turbines[a,b]	Density-weighted Area Adjustment for Searched Turbines[b,c]	Proportion of Turbines Searched
Frontier I	Spring	Moderate	0.857	0.662	1.00 (61/61)
	Summer	Low	0.298	0.360	0.61 (37/61)
	Fall	Low	0.857	0.662	1.00 (61/61)
	Winter	Low	0.857	0.662	1.00 (61/61)
Marble River	Spring	High	0.216	0.342	1.00 (70/70)
	Summer	High	0.183	0.301	1.00 (70/70)
	Fall	Low	0.216	0.342	1.00 (70/70)
	Winter	n/a	n/a	n/a	0 (0/70)
Mountain Wind I and II	Spring	Moderate	0.978	0.932	1.00 (67/67)
	Summer	Moderate	0.978	0.932	1.00 (67/67)
	Fall	Moderate	0.978	0.932	1.00 (67/67)
	Winter	n/a	n/a	n/a	0 (0/67)
Pinyon Pines I and II	Spring	High	0.999	0.939	1.00 (100/100)
	Summer	High	0.999	0.939	1.00 (100/100)
	Fall	High	0.999	0.939	1.00 (100/100)
	Winter	High	0.999	0.939	1.00 (100/100)
Shiloh I	Spring	Low	0.732	0.775	1.00 (100/100)
	Summer	Low	0.677	0.752	0.59 (59/100)
	Fall	Low	0.732	0.775	1.00 (100/100)
	Winter	Low	0.732	0.775	1.00 (100/100)
Wild Horse	Spring	Moderate	0.899	0.873	1.00 (149/149)
	Summer	Moderate	0.899	0.873	1.00 (149/149)
	Fall	Moderate	0.899	0.873	1.00 (149/149)
	Winter	Moderate	0.899	0.873	1.00 (149/149)

Area adjustments for the unviewable/unsearchable areas and proportion of viewable area are at turbines tested for incidental detection of eagles during detection trials conducted at the 6 study sites from June 27, 2021, through July 14, 2022.

[a]Cropland areas were considered unviewable/unsearchable during the summer season at Frontier I, Marble River, and Shiloh I; detection in these areas was assumed to be 0 until harvest occurred.

[b]n/a = not applicable; during periods where Operations and Maintenance staff were not routinely traveling the study site, detection trials were paused, and it was assumed no areas were searched until routine travel resumed.

[c]The density-weighted area adjustment can exceed the viewable proportion of the search area when carcass distribution is expected to be relatively high within viewable areas (see Hallingstad et al. [10]).

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season at each study site, with the greatest range occurring at Mountain Wind I and II (0–0.69), and the smallest range occurring at Marble River (0–0.11; Table 7). Given the long persistence times for raptors based on the persistence models used at 5 of our 6 study sites, the primary drivers of variability in incidental *g* were the detection probability and area adjustment. Mountain Wind I and II had relatively consistent incidental *g*'s between the 3 seasons in which detection trials were conducted (Table 7), as this study site had relatively consistent detection probabilities, persistence estimates, and searchable area in spring, summer, and fall. However, in winter, detection at Mountain Wind I and II was assumed to be 0 because frequent snowfall limited on-site travel by O&M staff and was also anticipated to obscure decoy (or carcass) presence on the landscape. Similarly, winter detection at Marble River was assumed to be 0; among the other 3 seasons, the incidental *g* was lowest at Marble River during spring due to reduced raptor carcass persistence during that season (see S1 Appendix). At Frontier I, the incidental *g*

Table 7. Overall probability of incidental detection.

Study Site	Season	Overall Probability of Incidental Detection (Incidental *g*)	90% Confidence Interval[a]
Frontier I	Spring	0.25	0.14–0.36
	Summer	0.12	0.07–0.19
	Fall	0.50	0.41–0.58
	Winter	0.47	0.37–0.57
	Overall	**0.33**	**0.29–0.38**
Marble River	Spring	0.06	0.03–0.10
	Summer	0.11	0.11–0.12
	Fall	0.10	0.07–0.13
	Winter[b]	0	n/a
	Overall	**0.07**	**0.06–0.08**
Mountain Wind I and II	Spring	0.58	0.48–0.67
	Summer	0.69	0.59–0.79
	Fall	0.62	0.52–0.71
	Winter[b]	0	n/a
	Overall	**0.47**	**0.43–0.51**
Pinyon Pines I and II	Spring	0.34	0.23–0.46
	Summer	0.45	0.33–0.57
	Fall	0.37	0.27–0.47
	Winter	0.25	0.15–0.37
	Overall	**0.35**	**0.30–0.41**
Shiloh I	Spring	0.24	0.16–0.33
	Summer	0.42	0.34–0.51
	Fall	0.40	0.30–0.51
	Winter	0.30	0.21–0.40
	Overall	**0.34**	**0.30–0.39**
Wild Horse	Spring	0.48	0.37–0.60
	Summer	0.21	0.14–0.28
	Fall	0.16	0.08–0.27
	Winter[c]	0.28	0.18–0.39
	Overall	**0.28**	**0.24–0.33**

Overall probability of incidental detection (incidental *g*) during detection trials conducted at 6 study sites from June 27, 2021, through July 14, 2022. Turbines were assumed to be visited at least once per month during the study period.

[a]n/a = not applicable

[b]No winter trials were conducted at Marble River and Mountain Wind I and II during the winter season as these study sites were inaccessible due to snowfall.

[c]One winter trial was missed at Wild Horse due to snowfall prohibiting access.

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was lower during the active crop period (0.12 [90% CI 0.07–0.19] in summer) than other seasons (0.25 [90% CI 0.14–0.36] to 0.50 [90% CI 0.41–0.58]; Table 7), but the effect was decreased by the insensitivity of the density-weighted area adjustment to reduced viewable area. For both Shiloh I and Frontier I, higher viewshed complexity during the spring season resulted in lower detection probabilities and, therefore, decreased overall probabilities of detection in this season (0.24 [90% CI 0.16–0.33] and 0.25 [90% CI 0.14–0.36], respectively) relative to fall and winter. Pinyon Pines I and II had its lowest incidental *g* in winter, when detection probability was lowest, while Wild Horse had its highest incidental *g* in spring, when both carcass persistence and detection probabilities were highest.

Discussion

We found O&M staff are successful at detecting large carcasses. O&M staff making regular turbine visits were capable of incidentally detecting approximately 1 out of every 2 decoys at our study sites, on average. Detection probabilities exceeded 0.25 at all study sites, reaching as high as 0.78. In a review of publicly available data from wind energy facilities, Bay et al. [37] found searcher efficiency ranged from roughly 0.43 to 1.0 for large bird carcasses (e.g., mallards, rock pigeons [*Columba livia*]) in 26 fatality monitoring studies administered by third parties, with a mean searcher efficiency of approximately 0.74. Our results indicate incidental detection by trained and diligent O&M staff can, under ideal conditions, approach detection probabilities resulting from eagle fatality monitoring studies employing transect and other more time-intensive search methods. Further, our results are congruent with a review of eagle fatalities in which the majority of eagle carcasses were detected incidentally during routine activities at wind energy facilities [3].

The true benefit of incidental detection requires calculation of *g*, which facility operators can then use to calculate fatality estimates and evaluate permit compliance. The *g* accounts for other sources of bias inherent with fatality monitoring, including the probability of a carcass persisting through the search interval and the proportion of carcasses that occur within searched areas. The annual incidental *g* at each study site ranged from 0.07 to 0.47, with seasonal detection probabilities ranging from 0 to 0.69. Our study sites covered a wide geographic range and included a variety of landscape conditions representative of many wind energy facilities. Combining all study sites, the average incidental *g* in our study was 0.31. In some circumstances, incidental *g* approached or exceeded *g*'s attainable through traditional standardized search methodology used in general bird and bat fatality monitoring (e.g., 30% of turbines searched out to tip-height radii using 6-m transect spacing results in a maximum *g* of 0.30; see Strickland et al. [38]). These incidental *g*'s were achievable because eagle carcasses are large, tend to be highly visible, and have long persistence times; incidental *g*'s for smaller taxa with shorter persistence times are unlikely to exceed *g*'s attainable through traditional standardized search methodology.

Our study shows that quantifying the incidental *g* is possible and can contribute to a better understanding of a facility's direct impacts on eagles. A potential advantage of incidental detection is reduced third-party monitoring burden placed on facility operators. Standardized searches are labor intensive, particularly if prescriptive monitoring requirements for regular searches of large areas underneath all turbines were necessary to meet the target *g* for compliance under an ETP [17–20]. Traditional monitoring often requires at least 2 hours of labor per turbine search and mobilization of a third party for monitoring [38]. Another advantage of incidental detection is that O&M staff are on site for the life of the facility, potentially offering long-term information on eagle and other large raptor mortality at all operating wind energy facilities. An improved understanding of eagle mortality would assist wildlife agencies and researchers aiming to evaluate how installed and future wind energy build-out could affect population trends of raptors [39–41].

Evaluating influences on incidental detection

Although there were multiple models with the same, lowest AICc among models of detection probability we considered, all of those models produced the same predictions, suggesting the underlying covariates of detection probability were related to distance from turbine (as represented by the density quartile variable), viewshed complexity, and (to a lesser extent) season. Density quartile was 1 of 2 primary drivers of the ability of O&M staff to detect decoys placed in our study, as we expected. Decoys placed farther from turbine bases were less likely to be detected, a trend consistent with the distance effect on detection found when testing a scanning search methodology [10]. This pattern was generally consistent within each viewshed complexity class, with some variability in the pattern imparted by the interaction effect of season and viewshed complexity. However, detection probabilities across viewshed complexities overlapped by density quartile. For example, detection probabilities within the far density quartile (more than 61 m from turbine bases) ranged from 0.01 to 0.36, whereas detection within the near density quartile (less than 33 m from turbine bases) ranged from 0.05 to 0.68. These results suggest viewshed complexity has a larger impact on incidental detection probability than distance from turbine.

The second main factor explaining detection probability by O&M staff was an interaction term containing viewshed complexity and season. The mechanism underlying the relationship between season and viewshed complexity with incidental detection probability is not readily apparent. In all seasons, incidental detection probability decreased as viewshed complexity increased. On average, decoys placed in low viewshed complexity areas were detected about twice as often as those placed in moderate viewshed complexity areas (average of modeled detection probability within viewshed complexity class was 0.64 and 0.33 for low and moderate, respectively), and detected 4 times more often than those placed in high viewshed complexity areas (0.64 versus 0.16). Even when considering distance from turbine, detection probabilities for decoys were consistently higher in low viewshed complexity sites than in moderate viewshed complexity sites. In other words, a decoy placed more than 61 m from a turbine base in low viewshed complexity had a greater detection probability in most seasons (summer was the exception) than a decoy placed less than 33 m from a turbine base in a moderate viewshed complexity. The pattern was not as strong when comparing moderate viewshed complexity to high viewshed complexity, but in most seasons, detection probability within moderate viewshed complexity was generally higher at greater distances from turbines than detection in high viewshed complexity at distances closer to turbines. Regardless of season, incidental detection probability should therefore be highest at facilities with predominately low viewshed complexity within 100 m of turbine bases.

How incidental detection probability within moderate and high viewshed complexity classes was influenced by season is less clear, however. It is possible areas falling into the moderate viewshed complexity areas in summer were closer to falling into the low viewshed complexity class compared to other seasons; this would explain why detection probability in moderate viewshed was higher in summer compared to the other seasons. Similarly, areas falling into the high viewshed complexity areas in spring may have been closer to falling into the unviewable/unsearchable category than in other seasons, thereby leading to lower detection probability within high viewshed complexity areas during spring. Our analysis shows that viewshed complexity better explains variation in incidental detection across the entire dataset, an intuitive result as detection probability is not expected to be driven by calendar date. Nonetheless, seasonal changes in viewshed complexity (and area adjustment, see below) are important to consider when determining potential influences on incidental detection. Our viewshed complexity classes only offer a coarse categorization of land cover conditions, and our season dates were approximations of when major changes in land cover due to snowfall or agricultural activity would occur (while also attempting to make seasons relatively equal in length). Improved resolution of viewshed complexity categories and a better understanding of how viewshed changes throughout the annual cycle, particularly at facilities with cropland areas, would provide clarity on the relationship between viewshed complexity and season with incidental detection probability. Furthermore, improved resolution of viewshed complexity changes through the annual cycle would facilitate a more balanced application of decoy trials across seasons and viewshed complexity classes, which would strengthen the inference gained from modeling drivers of incidental detection.

When O&M staff reported the activity they were participating in when a detection occurred, almost a third of all decoy detections were made while driving through the study sites. Eagle carcasses are large and can be highly visible on the landscape in certain conditions; it is important that area adjustment calculations include all areas within a minimum of 100 m of turbine bases that are visible from roads traveled by O&M staff. As turbine sizes increase and the distribution of carcasses may become more widely spread under larger turbines, operators of new facilities may want to extend the search area along roadsides to account for detections made in these areas by O&M staff while they are driving. Another 30% of detections occurred during unscheduled maintenance activities at turbines, either while technicians were on the turbine pad or while they were "up tower." Although we did not assess viewsheds from tower nacelles, it is possible that some proportion of these maintenance activity detections occurred from the nacelles. Encouraging the practice of a quick scan of the ground within 100 m of turbine bases while technicians are up-tower may be another way to increase the incidental *g*.

A critical component of effective incidental monitoring is to ensure O&M staff are educated and adequately trained in fatality detection and reporting procedures. Operators should encourage heightened awareness of fatalities and the benefits of incidental detection as an effective tool to ensure compliance with ETP conditions, while reducing the need for third-party involvement. Encouraging O&M staff awareness through proper training (e.g., developing a "search image") and incentivization can foster a culture of responsibility and O&M staff satisfaction in their ability to contribute towards ETP compliance. We found that O&M collected data were not reported consistently at each site throughout the entire year, limiting our ability to incorporate some data into our modeling efforts (e.g., O&M activity when detection occurred). Data reliability can be enhanced through periodic training and by testing carcass detection by O&M staff with detection trials. Regular testing of O&M staff may be needed throughout the life of an ETP, particularly for long-term ETPs that may authorize eagle take for up to 30 years. O&M staff turnover, changes in maintenance schedules, monitoring fatigue, and other factors that could influence incidental detection may arise over time.

Any carcass detection study design has the potential to result in detection bias, as searchers become aware they are being tested upon detection of the first "trial carcass" and may have heightened diligence. A larger monthly sample size was initially planned (approximately 20 placements per study site per month), but we reduced our sampling effort due to concerns expressed by USFWS regarding high decoy densities biasing O&M staff detection probabilities. The rate at which decoys were placed at sites was not intended to accurately mimic a realistic eagle fatality rate because our study was constrained by time, cost, and sample size requirements. Nonetheless, even at our smallest study sites, decoys were only placed at roughly 25% of a facility's turbines during each monthly trial and not all decoys were detected; thus, O&M staff were not detecting nor were decoys present at the majority of turbines O&M staff visited in any given month. Given the relatively infrequency of any 1 O&M staff member coming across a carcass during their workday and the extended study period, we believe our results are indicative of realistic incidental detection probabilities attainable by trained and diligent O&M staff under an ETP fatality monitoring situation.

Other influences on the overall probability of incidental detection (incidental *g*)

Incidental *g* can be affected by variability in detection probability, as well as patterns in carcass persistence and the area adjustment. Areas not visible from turbine bases or surrounding roads reduce incidental *g* by requiring an area adjustment; the magnitude of this effect will depend upon how far the unviewable/unsearchable areas are from the turbine bases. For example, if topography blocks view of an area more than 61 m from a turbine base, the impact on incidental *g* will be mitigated by reduced large carcass density at such distances (i.e., the unviewable/unsearchable area in this example would be expected to contain fewer carcasses than areas closer to the turbine base).

Seasonal effects can also influence detection probability by decreasing the effective search area. Snowfall and continual snow cover precluded O&M staff from adhering to their regular turbine visitation schedule at 3 of our study sites. When O&M staff are not routinely traveling the facility because conditions are not conducive to travel, detection probability is expected to be 0. Carcasses can be found once the snow melts, but quantifying the effect of such conditions on carcass condition and detectability fell outside the scope of this study due to funding and logistical constraints.

Another seasonal effect was seen when crops reached heights that prevented detection, which we treated as unsearchable/unviewable areas in our study. Wind energy facilities in predominately agricultural areas will face a similar challenge during the peak growing season as facilities dealing with winter closures. The impact on detection will be dictated by the length of these periods, and in the case of cropland, the extent of the cropland areas and the density of carcasses estimated to occur within them (as based on carcass distribution models). Facilities experiencing substantial inter-annual variation in cropland areas (e.g., a crop cycle rotation which includes fallow years) or snow depth may require area adjustments be recalculated annually to account for higher anticipated variability in search area conditions. For some facilities, eagle risk may not overlap challenging seasonal conditions, so researchers evaluating the potential of incidental detection at their facilities should focus on ground cover conditions during the seasons when collision risk is possible, or highest. Where seasonality in collision risk exists and can be quantified, eagle fatality estimation using EoA will account for (via weights in the Multiple Class Module) seasonally variable risk and weight the monitoring conditions during those seasons accordingly to develop *g*. For example, the incidental *g* would not be negatively impacted by ground cover conditions that may limit detection during the seasons when eagle use is absent.

Carcass persistence is also an important factor in *g*. In our study, we used the best available raptor persistence data. For 5 of our 6 study sites, this required applying persistence data from surrogate facilities in the same geographic areas and with similar land cover types. We assume the persistence data used in our analyses are representative of what we would observe if raptor persistence trials were conducted at these study sites. In the case of Marble River, we used persistence data from another northeastern wind energy facility located in forest habitat. The resulting probability of a carcass persisting through a 30-day interval at Marble River was 0.33 during the spring season; this persistence probability resulted in the incidental *g* during spring being 40% lower than during summer at Marble River despite having higher incidental detection (0.77 versus 0.57) in spring and a lower proportion of viewable area (0.301 versus 0.342) in the summer. Decreasing the search interval would result in more carcasses persisting until the next search round and would have a pronounced effect at facilities with low carcass persistence. If practicable, an operator could increase the incidental *g* at their facility by implementing more frequent turbine visitation (e.g., twice monthly).

Using the overall probability of incidental detection (incidental *g*) in fatality estimation

Estimating fatalities in a rare-event context (particularly when zero or few carcasses are expected to be found) is largely an exercise to determine how many fatalities could have occurred (at a given level of credibility), and higher detection probabilities are better able to constrain the range of estimated fatalities [13]. An evaluation of potential approaches that could be used to account for incidental carcass discoveries in EoA showed the upper bound on total fatalities (M*) for a given level of credibility can be strongly biased when incidental *g* is misspecified or poorly estimated and incidental detections are included in analyses [16]. However, if researchers can accurately estimate incidental *g*, they can use EoA to correctly adjust the number of eagles found (including 0) to an accurate M*. The value of M* could be used as a conservative estimate of fatalities during years in which standardized fatality surveys are not conducted, or incidental *g* could be used to determine an average *g* and calculate M* for a multi-year period during which standardized monitoring occurs in some years but not others. The *g*'s obtainable through standardized eagle fatality monitoring efforts are not yet well documented; however, previous simulations suggest even a relatively cost-effective standardized monitoring protocol could yield a *g* exceeding 0.50 in some conditions [10]. If we hypothesize 2 years of standardized monitoring provided a *g* of 0.60 and incidental detection provided a *g* of 0.30 in a year without standardized monitoring, failing to incorporate the contribution of incidental detection (i.e., a misspecification of incidental *g* as described in [16]) in the 3 years of a 5-year permit term with no standardized monitoring would result in a reduction of the overall average 5-year *g* from 0.43 to 0.24. Ultimately, such an approach would have a significant impact on the M* estimate (see below); thus, our study shows incidental detection can be an effective and efficient tool for gathering fatality monitoring data necessary to quantify eagle fatalities and help permittees document compliance with permitted take.

We applied the EoA estimator for a hypothetical facility where O&M staff conducting monthly turbine visits incidentally found up to 4 eagle carcasses over a 5-year permit term and had an incidental *g* within the general range of values observed during our study (Table 8). For example, if 2 eagle fatalities were found over the 5-year period, the value of M* at the 50th credible limit is 4 eagles (i.e., we can be 50% confident no more than 4 eagles were taken over 5 years) if the incidental *g* was $\geq$0.40 (Table 8). A permittee's ability to utilize the contribution of incidental detection to estimate eagle fatality rates in years without standardized eagle fatality monitoring has practical implications with respect to demonstrating eagle take permit compliance, quantifying the level of mitigation required, and likelihood for adaptive management actions if the facility were to exceed permitted take. Failing to factor in the contributions of incidental detection could lead to artificially inflated take estimates, potentially resulting in a permittee implementing costly and unnecessary measures to reduce take, additional mitigation requirements, and even permit suspension or revocation if permit take limits are exceeded.

Facility operators must evaluate ETP requirements when determining the value of incidental detection for their circumstances and determine the appropriate use of incidental detection

Table 8. Upper bound on mortality (M*) for *g* at the α = 0.50 credibility level.

Overall Probability of Detection (*g*)	Eagle Carcasses Found = 0	Eagle Carcasses Found = 1	Eagle Carcasses Found = 2	Eagle Carcasses Found = 3	Eagle Carcasses Found = 4
0.10	2	12	22	32	42
0.20	1	6	11	16	21
0.30	0	4	7	10	14
0.40	0	3	5	8	10
0.50	0	2	4	6	8

The upper bound on mortality (M*) at the α = 0.50 credibility level based on overall probability of detection (*g*) within the general range of values observed during the incidental eagle carcass detection study, and hypothetical carcass counts during a 5-year permit term, using the Evidence of Absence modeling framework.

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versus standardized fatality monitoring efforts used for fatality estimation. Our study shows incidental detection is a valuable tool that can supplement or, in ideal conditions (e.g., when viewshed complexity is relatively low, raptor persistence is long, and operations staff detect a large proportion of available carcasses), fully replace standardized fatality monitoring efforts.

Evaluating the potential for incidental detection at a wind energy facility

We believe our results show incidental detection can be part of a viable eagle fatality monitoring study design for ETPs, but facility operators should carefully evaluate their facility to assess the potential for incidental *g* to meet their monitoring objectives. This assessment involves a few simple steps. First, we recommend viewshed mapping as a preliminary step in assessing the viability of incidental detection at a given facility. Areas within 100 m of turbine bases that are not visible from pads or roads or have crop height and density that preclude detection (i.e., unviewable/unsearchable), will reduce the effective search area. Areas with high viewshed complexity, such as a tall, thick scrub-shrub plant community, will also reduce detection probability. The effect of lower detection probability on *g* will be larger if carcass density is expected to be high (i.e., areas within 61 m of turbine bases) within difficult to search or unsearchable areas. Conversely, if high viewshed complexity areas are more than 61 m from turbine bases, the effect of lower detection probability on *g* will not be as strong because less than 25% of carcasses are expected within these areas. We suggest that operators also consider winter access limitations at their facilities, as incidental detection can only occur when O&M staff are traveling to or visiting turbines. Seasonal and annual viewshed mapping would be needed if substantial access and vegetation changes occur throughout the year or between years.

Next, operators aiming to incorporate incidental detection probability into fatality estimation should be sure to maintain (or implement) a regular turbine visitation schedule. For our study, each study site had a standard operating procedure involving at least 1 visit to every turbine each month. This is a typical maintenance check schedule for wind energy facilities but is not applied universally. EoA requires a known search interval, as this ties into the probability of a carcass persisting until the next opportunity for detection. If practicable, an operator may also choose to increase turbine visitation (i.e., decrease their search interval) if the eagle take permit threshold supports maximizing detection. We also encourage all operators to use the best available raptor carcass persistence data to determine the appropriate carcass persistence estimate for their facility; in the absence of suitable raptor carcass persistence data, site-specific game bird persistence data can be adjusted and used in eagle fatality estimation [11].

Implications and next steps

Our study resulted in the successful application of a general field methodology in which an eagle carcass surrogate distributed throughout a facility can be used to measure the incidental *g* resulting from O&M staff performing their regular activities. Furthermore, the resulting incidental *g*'s support the inclusion of incidental detection into eagle fatality monitoring study designs and fatality estimation. Implementing a combination of standardized and incidental monitoring with the appropriate data quality standards, particularly in non-standardized monitoring years, can provide an efficient and viable fatality monitoring approach to assess consistency with ETP terms and conditions. Furthermore, at facilities with conditions that support high incidental detection probability (e.g., flat topography, low/sparse vegetation), standardized monitoring may not be required to meet compliance with ETP conditions. The field methodology described here could be applied at any wind energy facility, providing a cost-effective (less than $25,000 for a typical facility) approach for quantifying the contribution of incidental detection in an eagle fatality monitoring study at that facility.

Opportunities exist to refine our understanding of incidental carcass detection. First, we assumed decoys are a reasonable surrogate to evaluate detection of eagle carcasses. Eagle carcasses and parts are protected by federal law and are prioritized for Native American religious purposes, so obtaining authorization to use eagle carcasses for bias trials is unlikely. In the absence of eagle carcasses, researchers may choose to evaluate the suitability of decoys as a surrogate for testing detection by comparing detection probabilities between decoys and large raptor carcasses. Second, EoA incorporates a detection reduction factor (k) that describes how carcass detection changes between searches. In our study, we assumed a probability of 0.67 for this factor, which is the only published k currently available [36]. We did not evaluate the detection of partial carcasses and feather spots; we acknowledge this as a potential source of bias for these trials, because partial carcasses and feather spots likely have different detection probability compared to intact decoys. Of the 103 eagle fatalities in WEST's Renew database for which "physical condition" of the fatality was reported, 81 carcasses (79%) were at least partially intact and only 7 (7%) were found as feather spots [42]. Yet, heavy snowfall and other factors likely affect the degradation and detectability of eagle carcass remains. For the purpose of refining fatality estimates, we suggest further studies to estimate how eagle carcass detection may change between searches. Lastly, we measured incidental detection under a variety of landscape contexts and environmental conditions throughout a single year. However, incidental detection has been little studied, and we documented a wide range of overall probabilities of incidental detection in this study. Additional research will strengthen our inferences and add to our understanding of factors influencing incidental detection probability.

Supporting information

S1 Appendix. Additional details on estimating the average probability of carcass persistence for our study sites.
(DOCX)

S1 Table. Predominant viewshed complexity classes. Complexity classes by season during detection trials conducted at the study sites from June 27, 2021, through July 14, 2022.
(DOCX)

S2 Table. Incidental detection trial results among viewshed complexity classes. Trial results among viewshed complexity classes during incidental detection trials conducted at the study sites from June 27, 2021, through July 14, 2022.
(DOCX)

S3 Table. Incidental detection trial results. Incidental results by study site and season for field studies during detection trials conducted at the study sites from June 27, 2021, through July 14, 2022.
(DOCX)

S4 Table. Incidental detection trial results by operations and maintenance staff activity. Trial results by activity being performed by Operations and Maintenance staff at the time of detection during the detection trials conducted at the study sites from June 27, 2021, through July 14, 2022.
(DOCX)

S5 Table. Model selection results for incidental detection. Results using AICc for 18 models of incidental detection using 918 decoy placements during detection trials conducted at 6 study sites from June 27, 2021, through July 14, 2022. The term (1|Site) represents a random effect for site; all other effects are fixed. Originally, there were 64 different models; however,

when multiple models resulted in the same AICc value (and thus were different parameterizations of the same underlying model), we only included one model in the table below for comparison and interpretation.
(DOCX)

S1 File.
(INI)

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