Statistical advice for a solar power installation at Haldon Station, Cantebury, New Zealand.

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File history

This table shows the modifications made to the following report.

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Executive summary

Background

Lodestone Energy is proposing to construct a photovoltaic (PV) solar facility at Haldon Station (NZ) and Proteus was engaged to provide study design advice for an avian-mortality monitoring programme and a statistical review of the 'lake-effect hypothesis' (LEH).

Literature review

- LEH proposes that birds are vulnerable to collisions with solar facility structures because the reflective properties of solar panels can mimic the appearance of water bodies.
- Evidence for LEH is limited and held back by geographic and habitat biases (i.e., from facilities in southern California, Poland and South Africa), non-standardised data collection, and repeated use of the same data sets from facilities that are not representative of modern installations.
- Overall, avian interactions with solar facilities appear highly variable and context-dependent, varying with local species assemblages, habitat characteristics, and facility design.
- In particular, reported avian mortality estimates (due to LEH or otherwise) have been found to span several orders of magnitude across solar facilities.
- There is limited understanding of how these factors will interact within New Zealand systems.

Proposed monitoring design

A general design consists of the following three components. *Avian mortality surveys* are intended to be ongoing, while *Searcher efficiency trials* and *Carcass persistence trials* may be repeated periodically as conditions and circumstances change (e.g., seasonality, personnel or technology).

- *Avian mortality surveys:* Survey a portion of the site at set intervals, searching between and under solar panel rows to document and record any bird carcass finds along with their suspected species. Ensure that search type, or platform (e.g., humans, drones), matches those tested in *Searcher efficiency trials.*
- *Searcher efficiency trials:* Place known carcasses during avian mortality surveys to estimate, and compare, the underlying detection probability for intended search methods (e.g., humans, drones).
- *Carcass persistence trials:* Separate to avian mortality surveys, place and monitor avian carcasses over time to estimate scavenger removal and decay rates.

Simulations

Simulations were conducted to evaluate the expected performance of the monitoring protocol to detect, and estimate total, bird mortalities under a range of scenarios. Factors considered include survey methods, search effort and frequency, and bird mortality rates. Key points from the simulation study include:

- These simulations test estimations of avian mortality and searcher efficiency at a solar facility using scenarios based on detection probability estimates from published research using human searchers. Because the simulations incorporate a broad range of higher and lower detection values, the results are not limited to human-based searches and can reasonably be extended to alternative search methods that are expected to have a similar detection probability.
  - Drones have been suggested as a promising alternative for carcass-detection surveys; however, there is currently limited research quantifying their efficiency in this context. As a result, their comparative performance remains uncertain.
  - This project could provide an excellent opportunity to help determine the detection efficiency of drone-based searches.
- *Avian mortality survey:* Higher site coverage, or more frequent surveys, is necessary to document mortality and to produce reliable estimates of annual mortality rate.
  - This is particularly true for smaller birds, or, more specifically, birds with low detection probability and low persistence rate.
  - Furthermore, the documentation of no carcass finds is possible across a range of actual mortality rates (larger for smaller sized birds) given that carcasses are removed by scavengers and may be missed during surveys.
  - Estimated mortality rates with high confidence can be achieved given

sufficiently extensive survey covarage of the site, high searcher efficiency and carcass persistence rates.

- Similarly, given detection of no carcasses, high confidence in low annual mortality rates can be achieved when coverage and survey frequency are high, particularly when coupled with high search efficiency and carcass persistence rate.

- *Searcher efficiency trials:* More repeated trials with fewer carcasses each provide more accurate detection estimates.
- *Carcass persistence trials:* Shorter sample intervals reduce bias, which is important when persistence is low.

Recommendations

- *Avian mortality surveys:* Employ a minimum of weekly surveys, searching upwards of 12.5% of the site during each survey.
  - Documenting carcass size-class and suspected species is important, as mortality estimates are highly dependent on detection probability and carcass persistence, which vary with size.
  - If no carcasses are observed during monitoring, upper bounds should be calculated (e.g. from a 95% confidence interval) of potential mortality that is consistent with this observation given the survey effort and duration employed.
  - It is recommended that these simulations be re-examined with updated detection probability and persistence rates resulting from searcher efficiency and carcass persistence trials detailed herein to provide more accurate measures of monitoring performance that are directly relevant to the location of the proposed facility.
  - Currently, these simulations were based on detection probability estimate from human searchers and carcass persistence rates from studies performed outside of New Zealand, which may not be representative of the search type employed or carcass characteristics at Haldon. It is plausible that searcher efficiencies and carcass persistence rates will be higher at Haldon, such that monitoring will be more effective and mortality rates more tightly constrained. However, the degree to which this applies is currently unknown.
- *Searcher efficiency trials:* Use more trials with fewer carcasses to avoid biasing searcher behaviour. Adjust sampling intensity based on expected detection

probability.

- *Carcass persistence trials:* Implement a higher sampling frequency with fewer carcasses to avoid overwhelming local scavengers. Repeat trials and adjust intensity if scavenger community changes over time (e.g. through predator control).
- It is recommended that *Searcher efficiency trials*, incorporating potential search methodologies (e.g., humans and drones), and *Carcass persistence trials* be implemented pre-construction to obtain estimates of these factors that are specific to the site of the proposed solar facility, adn to evaluate the relative cost effectiveness of different search methods.

1. Background

This project supports the design and assessment of an avian mortality monitoring plan for a proposed solar energy facility from Lodestone Energy at Haldon Station in the Mackenzie District of New Zealand. Proteus was engaged to provide study design advice and to evaluate the statistical power to detect avian mortality rates under a suite of alternative monitoring scenarios. In addition, Proteus was asked to review existing literature on the 'lake effect hypothesis', which suggests that solar panels may attract birds due to their reflective properties mimicking water bodies, from a statistical perspective.

2. Literature review

2.1 Summary

This review focuses on the support for the LEH from a statistical perspective. The impact of solar facilities on bird communities remains relatively understudied compared to other methods of renewable energy generation. Existing evidence suggests that solar facilities are linked to highly variable mortality rates and ecological responses that depend strongly on local context. The high levels of variability in estimated avian mortality rates among solar facilities have been linked to differences in local species assemblages, habitat characteristics, and facility design.

LEH emerged from early observations suggesting that birds may mistake reflective, polarized solar panels for water, although initial reports do not provide clear evidence that birds are responding to polarized light.

Empirical support for LEH is limited, with few experimental studies focused on the topic. Overall, the evaluation of LEH is restricted by geographical biases in research, inconsistent monitoring and reporting, over-reliance on key datasets from facilities that may be unrepresentative of modern installation technologies, and a lack of direct experimental testing.

2.2 Solar energy generation and avian communities

With the rapid growth in renewable energy installations worldwide, there has been increasing interest in understanding their environmental impacts. One area of particular concern across several types of renewable facilities is avian mortality, as many bird species are especially sensitive to the habitat changes associated with

energy infrastructure (Dhunny et al., 2019). Despite this, research on the impact on avian communities at solar facilities has been, relative to some other renewable energy sources, under explored (Smith & Dwyer, 2016). Wind farms, in particular, have been the subject of numerous studies that have quantified bird collision rates and identified species most at risk in a range of settings (Drewitt & Langston, 2006; Marques et al., 2014). One of the earliest reported accounts of avian mortalities at a solar facility were made by McCrary et al. (1986). They documented carcasses found at Solar One, a concentrating solar power system, that, at the time, was the world's largest solar energy power plant. Based on their observations, they concluded that avian mortality at the facility was low and unlikely to have significant effects on local bird populations. Following this, there appears to be few peer-reviewed publications on this topic until a resurgence in the late 2010s (Gómez-Catasús et al., 2024). The literature that does exist is heavily concentrated in North American and arid environments, resulting in limited understanding of avian impacts in other ecological contexts (Anderson et al., 2025; Fleming, 2025).

Post-mortem analyses indicate that birds at solar energy facilities are exposed to multiple mortality pathways, which vary according to the method of power generation and the associated infrastructure. Frequently, the cause of mortality cannot be determined (Walston et al., 2016), and in some instances 'feather-spots' (a certain number of feathers within a defined radius) are being reported as carcasses (Kosciuch et al., 2020). When the cause of death can be determined, collision with facility structures (panels, lines, etc.) is frequently reported as the predominant source of avian mortality (Kagan et al., 2014; McCrary et al., 1986), typically inferred from the presence of broken bones. At facilities that utilise concentrating solar power, evidence of singeing is common, likely resulting from birds flying through concentrated beams of solar flux (Kagan et al., 2014; McCrary et al., 1986). Electrocution appears to be relatively rare within solar installations (Kagan et al., 2014; Kosciuch et al., 2020), although it is widely reported in more general studies of avian interactions with power lines (Kagan, 2016; Loss et al., 2014). Lastly, at sites that include evaporation ponds, drowning has also been identified as an additional mortality pathway (Jeal et al., 2019).

Across studies, estimated avian mortality rates (measured in terms of deaths per megawatt produced by the facility per year) vary widely, generally ranging from 1.7 to 22..9 birds/MW/year for PV facilities and 0.1 to 64.6 birds/MW/year for concentration solar power (Jeal et al., 2019; Kosciuch et al., 2020; Smallwood, 2022; Visser et al., 2019; Walston et al., 2016). Many of these estimates originate from North American

sites and arid ecosystems, limiting their generality, particularly to the New Zealand context given our avifauna and predator communities that are very different to those in North America. In contrast, a recent study from rural Poland documented no avian mortalities across six PV facilities over a two-year period (Oglęcki et al., 2025). Overall, solar energy facilities tend to perform favourably in terms of avian mortality, with rates that are comparable to or lower than those reported for wind energy and substantially lower than those associated with fossil fuel power plants, roadways, or buildings (Walston et al., 2016).

Reports of sub-lethal and indirect effects of solar facilities on avian populations are rare; however, they are becoming more frequent. As with mortality estimates, findings vary widely among locations. Several studies have reported an increase in avian abundance and diversity within solar facilities compared to nearby habitat (Copping et al., 2025; Golawski et al., 2025), which is often attributed to structure within the facilities creating novel habitats and enhanced foraging opportunities (Anderson et al., 2025). Conversely, other authors have reported declines in avian abundance and diversity (Ahmed, 2022; Jeal, 2017; van Heerden, 2020; Visser et al., 2019), while some have observed no measurable change (Young et al., 2025).

Collectively, the evidence suggests that impacts of solar facilities on avian communities are highly context-dependent, influenced by an interplay of geographic, taxonomic, ecological, and structural factors. Consequently, caution should be exercised when extrapolating findings to novel development contexts in New Zealand.

2.3   Origins of the 'lake effect hypothesis'

LEH emerged from this body of work. It proposes that birds are vulnerable to collisions with solar facility structures because of the reflective properties of solar panels can mimic the appearance of water bodies (Diehl et al., 2024; Fleming, 2025). More specifically, the hypothesis suggests that solar panels polarize light in a manner similar to the surface of water, producing visual cues detectable by birds and potentially leading them to mistake solar facilities as suitable landing sites.

The first known use of the term appears in a 2014 *Scientific American* article by John Upton (Diehl et al., 2024; Upton, 2014). The article summarised a report for the United States Fish and Wildlife Service (Kagan et al., 2014), which documented avian

mortalities recorded at three solar facilities in California. The hypothesis gained traction because the report noted that several waterbird species, that would not be expected to land in desert environments, were found dead across the three facilities (Kosciuch et al., 2020).

However, the original report by Kagan et al. (2014) does not explicitly argue that solar facilities attract birds through polarized light. The authors acknowledge that "water-like" reflective or polarizing panels present at the sites were hazards, but they appear to primarily reference these features in the context of attracting invertebrates rather than birds. They hypothesize that artificial features present in the solar facilities may draw invertebrate prey, which in turn attract insectivorous birds, creating a so-called "ecological trap", a system where organisms select areas that reduce their fitness relative to other available habitat (Hale & Swearer, 2016; Smith & Dwyer, 2016). Whether this form of indirect attraction is consistent with the LEH remains unclear in the literature, and authors have not always distinguished between these mechanisms.

Additionally, the authors caution that because carcass collection was opportunistic and unstandardised, and the lack of baseline avian abundance or background mortality rates, the data set could not be analysed statistically. Consequently, any conclusions drawn from the report should be treated with care, as it is unclear how representative the recorded mortalities are for the solar facilities, or how they compare to levels in the surrounding habitat. Furthermore, it should be noted that the report was based on data collected at facilities that used fixed-tilt panels and prior to the application of anti-reflective coatings on panels, and may therefore be unrepresentative of modern PV facilities (Kosciuch et al., 2025).

2.4   Evidence for the 'lake effect hypothesis'

Research that directly test the LEH remain limited, and relatively few peer-reviewed studies provide empirical tests of its core assumptions. In particular, we found very few experimental studies designed to test said assumptions.

The most substantial experimental work to date is presented in a report by Diehl et al. (2024) for the California Energy Commission, which explored a number of research questions related to the LEH. In one experiment, the authors exposed birds to artificial structures whose colours had been modified to alter the level of polarisation. Birds

showed a preference for visiting darker feeders and water baths that had higher levels of polarisation. However, this preference did not extend to simple panels placed upon the ground, suggesting that the response may be linked to foraging or water opportunities. In a second experiment, the authors demonstrated that two common utility-scale solar panel types (crystalline silicon and thin-film) can polarize visible light to degrees that approximate the degree of linear polarisation (DoLP) of water surfaces across viewing angles and distances that birds would realistically experience at desert solar installations. From a statistical perspective, however, the study design is not clearly described. Key details, including the sample size (both the number of panels and the number of recordings), the variability associated with their measurements (the report only includes scatter plots with undefined error bars), and the method used to compared the DoLP of the panels to that of water (including the source of the water measurements), are not provided.

A thesis by Grossweiner (2025) investigated whether birds use polarised light as a cue to locate water, but found that zebra finches did not reliably choose higher-polarization options. They attributed this to unsuccessful conditioning training. More broadly, there is some experimental evidence that birds use polarized light as an environmental cue. For example, migratory birds have been shown to use skylight polarization as one of many orientation cues (Able, 1989; Muheim, 2011; Munro & Wiltschko, 1995).

Evidence from survey-based studies is similarly limited. Beyond the mortality and diversity surveys discussed previously, relatively few survey-based investigations directly evaluate the LEH. In the same report, Diehl et al. (2024) describes radar-based survey they performed at two PV facilities in California, which found no conclusive evidence that these sites altered bird flight direction. However, south-bound birds were more frequently observed descending near midday, a pattern the authors suggested may reflect individuals seeking water or refuge in the regions extremely arid landscape.

Related survey efforts reported across Diehl et al. (2024) and Kosciuch et al. (2021) found substantial overlap in estimates of alive and dead avian species richness between solar facilities and nearby reference sites. They did note that aquatic bird carcasses were observed at solar facilities while absent from several reference locations in desert and grassland habitats, although the number of observed fatalities was low at both the solar facilities and references. To evaluate the strength of the statistical evidence for the number of observed aquatic bird mortalities at PV solar facilities being greater than those observed at reference sites in desert, grassland and agricultural habitat types, a restricted randomisation test was conducted using the mortality data

supplied in Appendix C of Diehl et al. (2024). Controlling for bird species and the site of the facility and associated reference site, the total number of fatalities was not significantly higher at solar facilitates than at reference sites (Table 2.1).

2.5   Limitations with the literature

A number of general limitations in the existing literature complicate the evaluation of the LEH:

1. Geographical bias: Most research has been concentrated in the United States, particularly in arid desert habitats (Fleming, 2025). Although newer studies are emerging from a broader range of environments, these indicate that avian responses to solar facilities are strongly context-dependent and can be highly variable between facilities, limiting the generalisability of earlier findings.

2. Inconsistent data collection: Many studies are reliant on data collected by solar energy facility staff, and the avian monitoring practices across these facilities can vary widely (Walston et al., 2015). Some installations seem to lack formal protocols altogether. Differences in survey methods, carcass definitions (e.g. how many feathers constitute a carcass), and analytical approaches reduces comparability across studies.

3. Over-reliance on particular datasets: Several studies have focused on the monitoring programs across facilities in California, and so data from these had been repeatedly used across studies. Kosciuch et al. (2025) noted that one dataset from a single PV facility had been used across eight publications and cited by nearly all studies discussing aquatic bird mortality. This dataset underpins much of the scientific discourse on the LEH despite originating from a facility that does not reflect the characteristics of modern installations.

4. Limited direct testing of the hypothesis: Very few studies explicitly evaluate the lake-effect mechanism itself, and controlled or experimental studies are especially rare, even the collection of baseline (i.e., pre-construction) mortality. As a result, many conclusions rely on indirect or correlative evidence rather than rigorous hypothesis testing and statistically-robust data collection methods.

Table 2.1: Total number of aquatic bird fatalities observed at solar facilities and reference sites across three habitat types, the observed difference (Facility − Reference) and the associated p-value from a restricted randomisation test.

Habitat	Facility	Reference	Difference	p-value
Desert	3	0	3	0.134
Grassland	1	0	1	0.493
Agricultural	5	6	-1	0.807

3. Proposed study design

3.1　Summary

This section proposes an integrated monitoring programme to estimate and interpret avian mortality across the facility's operational life, combining avian mortality surveys, searcher efficiency trials, and carcass persistence trials. Simulations show that performance varies strongly by carcass size and mortality rate, where size is effectively a proxy for different detection probability and carcass persistence characteristics given the observed range for birds in other systems.

Mortality of medium to large birds is commonly detected across many monitoring designs, whereas documenting or accurately estimating mortality in small birds requires high-effort designs. Accordingly, it is recommended that surveys are performed weekly (preferred) or bi-weekly (only when coupled with higher coverage), with ~12.5–25% site coverage per survey. To maximise the potential for detecting mortality, surveyed sections of the site should alternate between surveys so that every part of the site is searched at some point during the monitoring program. Maximising coverage and survey frequency (i.e., using drones) and search efficiency (e.g., using dog teams or high-resolution drone imagery) would provide benefits in terms of mortality detection and estimation, and in reducing the upper bound of plausible mortality rate given the observation of zero carcasses across surveys. Searcher efficiency trials should use more repeated trials with fewer carcasses to improve precision without signalling the test to observers, and persistence trials should prioritise higher sampling frequency because longer intervals bias daily persistence estimates downward, especially when persistence is moderate. As zero finds are plausible at low mortality, results should be reported with plausible upper bounds on annual mortality.

Given the lack of information on searcher efficiency and carcass persistence rates in the New Zealand context, and to avoid reliance on estimates from quite different

ecosystems, it is recommended that searcher efficiency and carcass persistence trials be conducted pre-construction to obtain relevant estimates for the local conditions, and to evaluate the relative benefits of different search agents (e.g., humans, dogs or drones) and their cost effectiveness. The simulation study could be refined once relevant estimates have been obtained to provide updated advice on optimal survey effort and frequency for the avian mortality surveys.

Furthermore, as the facility becomes operational, it is recommended that searcher efficiency and carcass persistence trials be repeated periodically to account for potential changes in conditions (e.g., seasonality, personnel or technology). This will enable avian mortality estimates to be updated with the most relevant information on detection probability and carcass persistence, and provid more accurate estimates of avian mortalities.

3.2 Field methodology

3.2.1 Overview

The following section describes three study designs that we recommend implementing prior to construction and over the operational lifespan of the facility. These are:

1. *avian mortality surveys*, which quantify the abundance and identity of bird carcasses found within the site;
2. *searcher efficiency trials*, which assess how effectively observers detect carcasses in the field; and
3. *carcass persistence trials*, which determine how detection probability changes over time as carcasses are scavenged or decay.

3.2.2 Avian mortality surveys

Avian mortality surveys are undertaken to estimate mortality rate, defined as the total number of birds that die within the confines of the facility per year. Mortality rate is

estimated through surveys of sections of the facility performed at set intervals (i.e., 7 days between surveys) with the aim of recording any bird carcasses found within the surveyed section per survey. Given expectations of imperfect searcher efficiency (see Searcher efficiency trials), carcass loss through scavenging or other removal (see Carcass persistence trials), and less than 100% survey coverage in space and time, the cumulative carcass count per year is a fraction (including 0) of the actual mortality rate. However, given information on the above factors, a plausible estimate of mortality rate can be produced given a set of observed carcass counts.

The first stage in setting up a monitoring design is to decide on how to divide the site into sections dependent on features that may have relatively lower or higher bird collision rates. Features may include perimeter fences, photovoltaic (PV) panel arrays, and transmission lines, amongst others. The analysis presented herein focuses purely on surveys in and around the PV panel arrays given their larger footprint and potential impact to wildlife. Whilst evidence from solar farms in California, USA (Smallwood, 2022), suggest that mortality rates are generally higher around PV panels when compared to perimeter fencing and generator tie-ins, supplementary surveys of non-PV features should be considered to capture project-wide mortality.

Given the lack of specific information on the layout of the facility, one potential approach would be to divide the 320 ha site into 32 equally sized (i.e., area = 10 ha, or 0.1 km^2) sections or blocks. Within each block, surveys would involve a systematic search of the area, with searchers traversing along rows of solar panels and searching for bird carcasses around and under each panel. This is equivalent to a strip-transect search, with transect width equal to the separation between adjacent solar panel rows. Assuming that panels are spaced at 4–5 meters apart, a comprehensive survey of each 10 ha block would require a minimum walking distance of 20 to 25 km (row spacings of 5 and 4 m respectively). If a two-person search team were to be employed, with each surveyor searching a different part of the block, then search times may average 5–6 hours assuming an average walking speed of 2 km h^{-1}. However, an equivalent search design could be achieved by any other search agent, defined as any person or object capable of providing information on carcasses present in an area, including drones or person and dog teams, so long as the monitoring design achieves the same coverage and search interval specified.

The exact arrangement of blocks should be informed by facility layout and may be irregular in shape. Following the searching of each block, the total area searched (if different from that intended) should be recorded, along with the surveyor name to

account for possible differences in search efficiency among individuals in subsequent analyses. If carcasses are found, then the identity (species or highest taxonomic resolution possible given carcass condition), location (latitude and longitude), and condition of each carcass found should be recorded. Carcass finds should also be photographed *in situ* and collected to avoid double counting in subsequent searches and for further inspection.

Each survey should consist of searches of a number of blocks, as described above, constituting a certain percentage of the entire facility area (e.g., 4 blocks = 12.5% coverage). Blocks searched in each survey need not be searched in the same day, with blocks divided among consecutive days dependent on the total number of search agents available and their daily search capacity. For example, 12.5% site coverage could be achieved by a team of two people surveying one of the four designated blocks each day over four consecutive days, or over two consecutive days with a team of four surveyors. As mortality may occur throughout the year, surveys should be performed at set intervals to provide a better estimate of year-round mortality. Survey intervals of 7 days have been suggested as best-practice on solar farms (Smallwood, 2022), but the optimal interval will likely depend on mortality rate and carcass persistence times (Jenkins et al., 2015). To ensure that each block is surveyed at least once, blocks searched in each survey should rotate from one set to another in subsequent surveys, with blocks assigned randomly within each set.

If surveys are performed as described above for a given duration, then the resulting data should consist of a series of counts, with a count for each block searched in each survey. Given information on searcher efficiency specific to the search agent, and carcass persistence, specific to bird size or type, daily mortality rates at the block level can be produced from observed counts by accounting for carcasses lost between survey occasions and missed detections. Daily mortality rate estimates can then be scaled up to mortality rates per year for the entire facility. More details on mortality rate estimation are provided in the Appendix.

3.2.3   Searcher efficiency trials

Searcher efficiency trials are undertaken to quantify the probability that the search method used in the mortality surveys will detect carcasses when they are present (i.e.,

detection probability). Carcasses may go undetected for a range of reasons, including: vegetation cover, carcass size, terrain, and variability in observer performance. Searcher efficiency trials can allow accurate estimation of the proportion of carcasses likely missed during surveys. Without correcting for detection probability, raw carcass counts would substantially underestimate true mortality.

The first step is to obtain carcasses that represent relevant size classes for avian species that may be expected to occur in the surrounding area. Commonly, birds are divided into small (30 g), medium (400 g), and large (> 1 kg) sized birds. However, these categories should be tailored to the local avifauna. Based on information provided by the Department of Conservation, the 18 species of most concern range in mean mass from about 35 to 2200 g. The source(s) of the carcasses will depend on local availability and regulatory permissions; however, domestic analogues are typically acceptable when wild carcasses cannot be used.

Carcasses should be assigned to random locations within the same area that routine mortality surveying occurs. Stratification can be applied if impacts associated with specific areas or structures are of interest. Each carcass should be assigned a unique identifier and its placement location, in terms of GPS coordinates, should be recorded. Placement should occur shortly before a scheduled mortality monitoring survey. When placed, each carcass should be positioned in a "natural" posture that does not artificially alter visibility. Furthermore, disturbance to the substrate or vegetation surrounding the placement from individuals placing the carcass should be kept to a minimum so that there are no additional cues that may lead searchers to find the carcass. Studies of search efficiency on wind-farms have used drones for this purpose, but this may be impractical when placing carcasses in or around solar panels. Searchers conducting the surveys should be unaware of these locations, or that the efficiency trial is occurring, so that search effort is similar to that used in regular surveys.

During the survey, searchers should follow the standard protocol described above. Following the survey, the agent(s) responsible for the searcher efficiency trial should revisit each carcass location and confirm whether they were detected. Any carcasses missed by search agents should be removed from the system at this point to avoid confusion with genuine fatalities during subsequent monitoring.

Searcher efficiency rates can then be estimated using the number of carcasses found compared to the total placed out. Analyses can be stratified by variables like carcass size class or searcher identity where appropriate.

3.2.4   Carcass persistence trials

The purpose of carcass persistence trials is to quantify how long avian carcasses remain detectable in the field. This information is essential for producing accurate estimates of mortality from the main carcass search surveys. Carcasses discovered during these surveys typically represent only a subset of the total mortalities at the site, as some carcasses can be removed or obscured before they have an opportunity to be found. Scavengers such as introduced mammals and select bird species may remove carcasses completely or aid in their decomposition over time, which can reduce carcass visibility. These impacts are often highly specific to the local weather conditions, habitat types, and scavenger communities. For this reason, persistence trials generally need to be conducted on-site to accurately estimate rates of carcass removal or loss and allow for appropriate correction in mortality estimates.

The carcasses will need to be sourced with respect to representative size classes outlined in the searcher efficiency methodology. For these trials, however, carcasses do not need to be placed strictly within the search area, provided they are placed in locations with comparable habitat and environmental conditions. This approach ensures that the trial accurately reflects the range of conditions likely to influence carcass persistence across the survey area.

The carcasses should again be placed in a natural manner to avoid altering their visibility to potential scavengers. Each carcass must be assigned a unique identifier and have its GPS coordinates recorded. Following deployment, each carcass should be revisited at predetermined intervals, or until it is no longer present. At each check, observers should record whether the carcass is present, note any changes in its condition (e.g. using a standardised categorical scale), including taking photographs at each check occasion, and document any evidence of scavenging. In the event that a carcass is missing from it's initial location, a search of the surrounding area within a radius of up to 100m of the original location, should be performed to check that the carcass hasn't been partially scavenged and moved to a nearby location. These repeated observations allow the fate of each carcass to be monitored over time.

As an alternative to manual revisits, camera traps can be deployed with the carcass in view. Camera traps can more easily provide higher temporal resolution and can help identify scavenger species through motion-triggered images or video. However, they

require greater post-processing effort compared to manual checks.

3.3   Simulation methodology

3.3.1   Avian mortality surveys

Avian mortality survey simulations were performed by simulating the separate processes of (i) mortality occurrence, (ii) carcass persistence and loss given initial mortality, and (iii) carcass finds given surveys of specific areas. Simulation state was updated on a daily schedule, updating the number of carcasses across the site, followed by updating the state of each carcass, simulating carcass losses via scavenging, and finally carcass finds if a survey happened on a particular day. Each simulation was performed for a total of five years (1825 days) as it was anticipated that initial monitoring and reporting may be desired over this timeframe. It also allowed for simulation of reporting carcass finds, and mortality rate estimation after one, two, and five years of monitoring, allowing for assessment of monitoring performance according to duration. Further details of the simulation routine are given in the Appendix.

Simulation variables

The simulation used to evaluate monitoring design performance depends on a range of variables including those associated with survey design (site coverage, survey interval), to mortality rate and carcass characteristics (searcher efficiency, carcass persistence rate). For each variable a range of values was identified based on known rates and recommendations for monitoring of solar farms from existing studies. The values chosen for each variable are given in Table 3.1.

For each variable we chose low, middle, and high values, where the middle values were informed by previous studies.

- *Coverage:* 20-30% has been cited as a good level of coverage in the literature (Jenkins et al., 2015; Visser et al., 2019), and appeared to be the most frequent coverage at solar farms in the USA (Smallwood, 2022)
- *Survey interval:* 7 to 28 days have been performed at solar farms in the USA (Smallwood, 2022)
- *Annual mortality rate:* little is known about mortalities on solar farms in New Zealand, but the expectation is that mortality rates will be lower than those

where monitoring has been performed in the USA, which serves as the bulk of known mortality estimates for solar farms worldwide.

- Lowest annual mortality rates from solar farms in California (the Desert sunlight facility) are equivalent to 0.54 birds/ha/year, which when scaled to Haldon (320 ha) gives an annual mortality rate of 174 birds (Smallwood, 2022).
- A middle mortality estimate was therefore chosen to be 50 birds per size class per year (150 total). This should not be taken to imply that mortality at Haldon would be of a similar magnitude, as it is only used here as a basis for evaluating monitoring design performance given values identified elsewhere. To test how well monitoring performs under lower mortality, simulations were also performed with annual mortality rates of 10 birds per size class per year, and 1 bird per size class per year, with the lowest value used to examine monitoring design performance in the most extreme low mortality range. An additional high mortality scenario of 100 birds per size class per year was also explored, although much of the results focus on the more probable lower mortality scenarios.

- *Searcher efficiencies:* These were selected based on a review of search efficiencies and carcass persistence rates at energy infrastructure facilities (Barrientos et al., 2018).

    - Search efficiencies were chosen for three different size-classes, representative of a 20-30 g bird (small), 300-400 g bird (medium) and 1100 g bird (large).
    - Search efficiencies that were higher or lower by 10 percentage points compared to the mid point value were also explored.
    - These search efficiencies were specific to a human observer; however, it should be made clear that these rates could be applied to any other platform or search agent, so long as the realised search efficiency by that agent matches that rate.

- *Carcass persistence rates:* These were selected based on the same review used to inform search efficiency rates (Barrientos et al., 2018).

    - As for search efficiency, daily persistence rates were identified for relevant sizes for each size-class to represent the middle estimate of daily persistence rate.
    - Higher and lower values were produced by calculating the daily persistence rates that would result in 10 percentage point difference in persistence after 3 days.

Table 3.1: Variables included in monitoring design evaluations.

Variable	Description	Size class	Values	Units
Coverage	Proportion of site searched in each survey		6.25, 12.5, 25, 50	%
Interval	Interval between surveys		4, 7, 14, 28	days
Mortality rate	Mortality rate for each size class for the entire facility		1, 10, 50, 100	birds/year
Search efficiency	Probability of finding a carcass given it is present in the survey area	Small	30, 40, 50	%
		Medium	60, 70, 80	%
		Large	70, 80, 90	%
Persistence rate	Probability that a carcass persists from one day to the next	Small	78, 87, 83	%
		Medium	86, 90, 94	%
		Large	92, 96, 99	%

Simulations were performed for every possible permutation of the values presented in Table 3.1, representing a range of monitoring design and mortality scenarios. For each scenario, a total of 500 simulations were performed to evaluate different possible outcomes from each.

It should be noted that the results obtained for alternate size-classes are only due to differences in searcher efficiency and persistence rate among sizes. Therefore, size-classes can be considered as scenarios of low efficiency – low persistence (small), mid efficiency – mid persistence (medium), and high efficiency – high persistence (large) given the observed range across bird sizes in other systems. As such, the results presented for any size-class can be directly transferred to any particular scenario as long as the corresponding searcher efficiency and carcass persistence rate match those specified (i.e., Table 3.1). This provides added flexibility when interpreting and applying the results, as searcher efficiencies and carcass persistence are currently unknown for the Haldon site. That being said, results are presented in terms of size-classes as these are the most commonly used descriptor of differences in searcher efficiency and persistence rate in studies of avian mortality surveys.

Mortality estimation and monitoring design performance

For each simulation, the resulting carcass counts were analysed to produce an estimate of annual mortality, in addition to whether any carcasses were documented by the given monitoring design throughout it's duration (1, 2, and 5 years of monitoring). This was performed independently for each size-class given differences in searcher efficiency and persistence rate of different body sizes.

The process for calculating mortality estimates from survey counts is provided in the Appendix. Estimates of annual mortality rate, denoted by $\hat{M}_s$ (where s indicates carcass size class), along with their 95% confidence interval were estimated for each simulation, and then aggregated across simulations for a given monitoring scenario.

Three different metrics were computed for each monitoring scenario to assess monitoring design performance given the coverage and interval between surveys, and rates assumed for searcher efficiency, carcass persistence, and annual mortality.

The first was the proportion of simulations where the monitoring design found any carcasses. This was deemed a relevant measure of monitoring design performance as the ability to document mortality (or not) of any kind, given that mortality has occurred, should be of primary importance.

Secondly, the proportion of simulations where the annual mortality estimate was within half to double the "true" annual mortality rate. This serves as a general measure of whether the monitoring design can produce estimates of mortality that reasonably capture the true underlying rate of mortality.

Finally, the average coefficient of variation (CV) of the annual mortality estimate. This metric gives an indication of the relative uncertainty of the mortality estimate for a given monitoring scenario, with lower values indicating lower uncertainty (i.e., more precise mortality estimates) and better monitoring performance. CV was calculated in each simulation as the mortality estimate confidence interval half-width divided by the mean. Given that some simulations resulted in zero carcass counts across the duration of monitoring, and thereby a mean mortality estimate of zero, this measure was only calculated for simulations resulting in non-zero counts. The metric was then calculated as the average CV across all simulations that resulted in non-zero counts.

Exploration of plausible mortality estimates given no carcass observations

Given that mortality rates may be low, in combination with carcasses being removed by scavengers and missed by search teams, it is plausible that monitoring may result in zero observations of bird carcasses. To explore this, a series of additional simulations were performed for a subset of monitoring scenarios (6.25 to 25% coverage, 7-day search interval, mid-values for searcher efficiency and persistence), but varying annual mortality rate from 2 to 100 birds per year per size class. For each monitoring design, 500 simulations were performed, and in each simulation it was recorded whether or not bird carcasses had been found after 1 year and after 2 years of monitoring. From this, the proportion of simulations finding no carcasses was calculated for each mortality level. This can be interpreted as an indication of the likelihood of finding no carcasses, given that mortality occurs at a known rate.

In addition, in the event of observing no carcasses, given a sample size of n observations, it is possible to assign a plausible upper limit on mortality given that outcome. In simple terms, this involves evaluating the likelihood of obtaining n observations of 0 given some non-zero mortality rate, and comparing this across alternate proposed mortality rates. As the proposed mortality rate increases, the relative chances of observing 0 carcasses decreases. Given that, it is possible to identify a plausible upper bound on mortality based on some desired degree of confidence about the actual mortality rate (i.e., the upper 95th percentile of mortality estimates). Plausible upper limits on mortality given no carcass observations are presented for monitoring designs utilising 4, 7, and 14 day search intervals, searching 6.25% to 50% of the site during each survey after monitoring for 1 and 2 years. Details regarding these calculations are presented in the Appendix.

3.3.2   Searcher efficiency trials

This simulation is designed to evaluate how three factors (i.e. the number of carcasses, the number of trials, and the baseline detection probability) influence the estimation of a search agent's carcass detection probability.

For each searching trial, the number of detected carcasses is simulated using a binomial distribution, where the number of trials (n) is equal to the number of carcasses placed out, and the success probability (p) corresponds to the baseline

detection probability. For each simulation run, the estimated detection probability is calculated as the total number of carcasses detected across all searching trials divided by the total number of carcasses deployed.

The parameters that were manipulated were:

- *Detection probability*
    - Allowed for three possible values: 0.3, 0.6, and 0.9
    - These are based on the two most extreme detection estimates (in either direction) used in the avian-mortality survey simulations, with an intermediate value included to represent a moderate level of searcher performance.
- *Number of carcasses placed out*
    - Allowed for three possible values: 5, 10, and 25
    - These are based on providing a reasonable range. While these likely exceed the number that would typically be found on site, some compromise is needed between realism and adequate replication.
- *Number of trials per searcher*
    - Allowed for three possible values: 1, 5, and 10
    - This range should reflect realistic searcher experience levels, from new agents to more seasoned searchers.

The simulation was run for 1,000 iterations per scenario. With 27 total scenarios (3×3×3), this resulted in 27,000 simulation runs in total. Estimated detection rate and CV were calculated for each scenario. Root mean squared error (RSME), which is the squared root of the average squared difference between the estimated and simulated detection rates, was also calculated as a measure of estimation accuracy.

3.3.3   Carcass persistence trials

This simulation was designed to assess how the number of carcasses, the sampling interval, and the baseline persistence rate influence the accuracy of estimated persistence probabilities.

On each sampling day, the number of carcasses that persist (i.e., remain present at the site) is simulated using a binomial distribution. The number of trials (n) is set to the

number of carcasses initially set out, and the success probability (p) is defined as the baseline daily persistence probability raised to the power of the number of days since the previous sampling event. This calculation yields the probability that a carcass persists over the interval between sampling events.

At each sampling day, the estimated persistence probability is calculated as the number of surviving carcasses divided by the number of surviving carcasses at the previous sampling day. For each simulated data set, an overall estimate of persistence probability is then obtained by calculating the mean across all sampling days on which removals occurred.

For all scenarios, the total sampling window was fixed at 45 days.

The parameters that were manipulated were:

- *Daily persistence probability*
    - Allowed for three possible values: 0.78, 0.885, and 0.99
    - These are based on the two most extreme daily persistence rate estimates (in either direction) used in the avian-mortality survey simulations, with an intermediate value included to represent a moderate probability of daily persistence
- *Number of carcasses placed out*
    - Allowed for three possible values: 5, 10, and 25
    - These are based on providing a reasonable range. While these likely exceed the number that would typically be found on site, some compromise is needed between realism and adequate replication.
- *Sampling interval in days*
    - Allowed for three possible values: 1, 3, and 5
    - This range represents feasible monitoring frequencies for operational surveys.

The simulation was run for 1,000 iterations per scenario. With 27 total scenarios (3×3×3), this resulted in 27,000 simulation runs in total. Estimated persistence probability, CV, and RSME were determined for each scenario.

3.4   Simulation results

3.4.1   Avian mortality surveys

Results for monitoring design performance are broken down into three sections.

The first evaluation examines metrics of monitoring design performance after one year of monitoring (similar results for two years and five years are given in the Appendix), with a specific focus on coverage and survey interval. Whilst one year is a limited amount of time, evaluating performance for this duration provides the strictest test of monitoring performance, and may be relevant to anticipated reporting timeframes for the first operational year of the facility. To focus on survey coverage and interval, these evaluations were limited to simulations with the mid-point values for search efficiency and persistence, but explicitly explores how much the results vary among bird size-classes and under different assumptions of mortality rate. From this initial evaluation, a subset of monitoring designs are selected to be explored in subsequent analyses.

The second section examines how monitoring design performance varies with alternate assumptions for search efficiency and persistence rate. This was deemed important given the lack of knowledge surrounding these values for solar facilities in New Zealand.

The final section explores possible mortality rates given the observation of no carcasses for a subset of monitoring designs at one and two year durations.

As a reminder, for each scenario the following metrics of monitoring design performance are explored:

1. Probability of finding any carcasses throughout monitoring duration $(Pr[\sum C > 0])$.
2. Proportion of simulations where the mortality estimate was within half to double the true mortality rate $(Pr[0.5M_0 < \hat{M} < 2M_0])$.
3. The average uncertainty of annual mortality estimates, expressed via the mean coefficient of variation $(CV[\hat{M}])$.

Here, the reader is reminded that bird size-classes are functionally representative of alternate assumptions concerning searcher efficiency and carcass persistence rate (small = low efficiency & low persistence, medium = mid efficiency & mid persistence, large = high efficiency & high persistence), and not necessarily as strict standards to be applied to all birds in all contexts. As such, any of the size-class scenarios could apply to any particular bird or bird type, so long as the search efficiency and carcass persistence rate are a close match for the realised rates for that bird type. However, size-class descriptors are used throughout the results as size is typically the biggest determinant of differences in searcher efficiency and persistence rate within any given location.

Probability of documenting mortality

Examining the probability of documenting any mortality illustrates the importance of bird size (Figure 3.1). For large-sized birds, the probability of documenting mortality was high for the majority of monitoring designs across all mortality rates, and was only below a reasonable standard of 0.8 for low coverage, high survey interval designs. At the lowest mortality rate investigated, constituting 1 mortality per year per size class, probability of detection was low for all of the monitoring designs for small birds, but were above 0.5 for medium and large-sized birds for the high coverage high frequency designs (Figure 3.1). At low mortality rates (10 birds per size class per year) probabilities of documenting mortality for small carcasses was less than 0.5 for most monitoring designs, with only the most labour-intensive design (50% coverage, 4 day survey interval) achieving probabilities greater than 0.8. Prospects were better for detection of mortality for medium sized birds when mortality rates are low, although monitoring designs with search intervals of 28 days performed poorly irrespective of coverage.
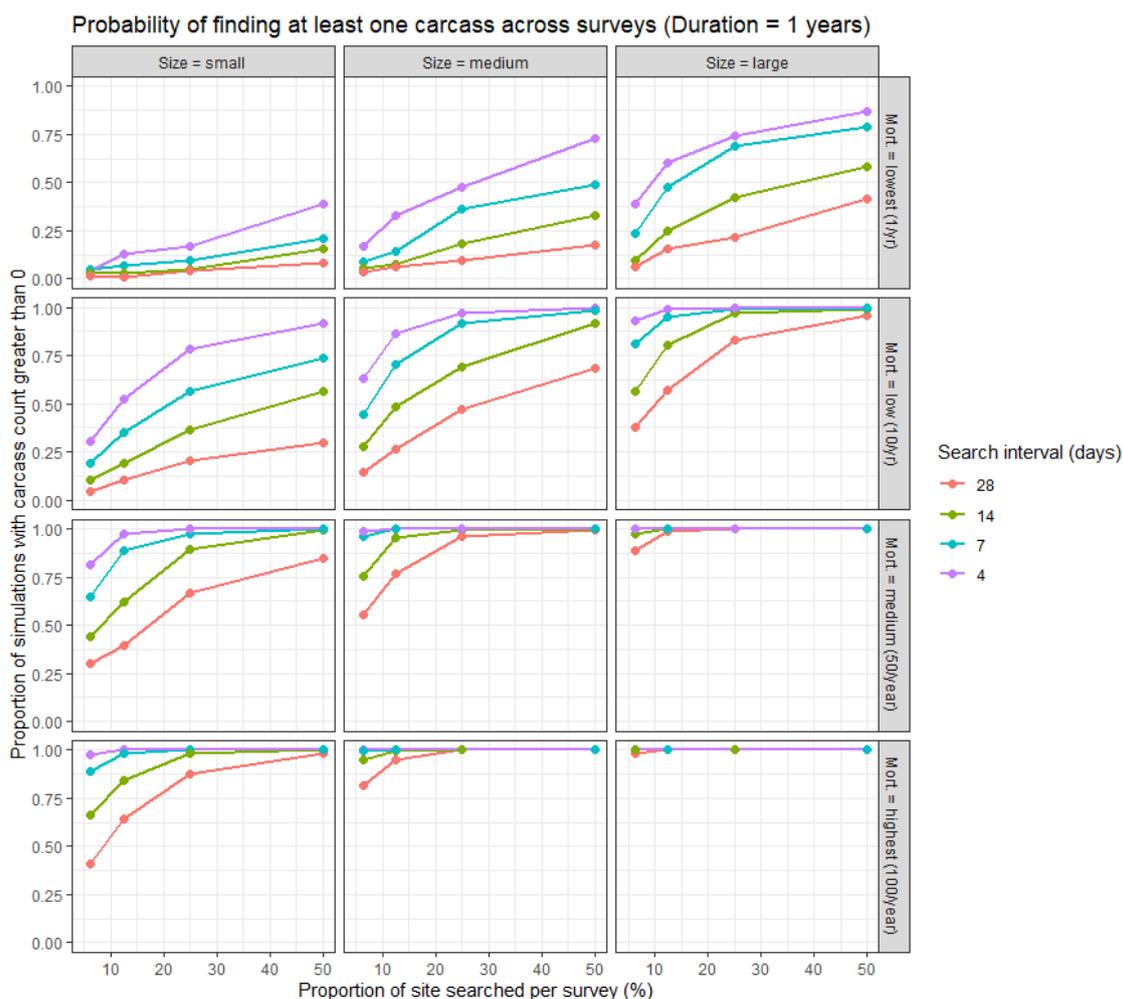
Figure 3.1: Probability of finding any carcasses plotted according to the proportion of the site searched (coverage) and survey interval for small, medium and large sized birds across a range of annual mortality rates.

Defining a minimum standard that monitoring should have a 50% chance of documenting mortality when mortality is low (10 birds per size class per year) for small-sized birds after one year would restrict monitoring designs to those with 4 (coverage $\geq$ 12.5%), 7 (coverage $\geq$ 25%) or 14-day (coverage = 50%) survey intervals. For medium-sized birds this same target is achieved for the majority of designs (Table 3.2). Setting a more rigid standard that monitoring should achieve a 80% chance of documenting mortality, limits designs to only the most comprehensive for small birds, but is attained for a broader range of designs when focused on medium-sized birds (Table 3.2).

Table 3.2: Minimum survey coverage required to meet separate standards of 0.5 or 0.8 probability of documenting mortality after one year of monitoring, given that mortality occurs at a low rate (10 birds per size class per year) for small, medium, and large bird carcasses.

Size class	Interval (d)	Min coverage (%) required for	
		Pr(C>0) > 0.5	Pr(C>0) > 0.8
Small	4	25	50
	7	50	None
	14	None	None
	28	None	None
Medium	4	6.25	12.5
	7	12.5	25
	14	25	50
	28	50	None
Large	4	6.25	6.25
	7	6.25	6.25
	14	6.25	12.5
	28	12.5	25

Reliability of mortality estimates in replicating true mortality rates

Patterns emerging from the analysis of whether mortality estimates were within half to double the true mortality rate after one year of monitoring were broadly similar to those shown previously for the probability of documenting mortality if it occurs, with a strong influence of body size and underlying mortality rate (Figure 3.2). For the lowest mortality rate of 1 bird per size class per year, none of the investigated monitoring designs performed well when estimating mortality. This was largely due to the fact that the majority of designs found either 0 or 1 carcass during the first year of operation, which provides limited information for estimating mortality. For small birds at low mortality rate, few of the designs investigated had a good probability of producing mortality estimates within half to double that of the actual mortality, primarily due to the dominance of simulated surveys that failed to find small birds. Monitoring designs performed better for medium-sized birds compared to small when mortality rates were low, although only higher effort designs (Table 3.3) achieved a 50% chance that mortality estimates were within the 0.5 to 2 range. At higher mortality rates, estimation of mortality generally improved, although challenges remained for small sized birds.
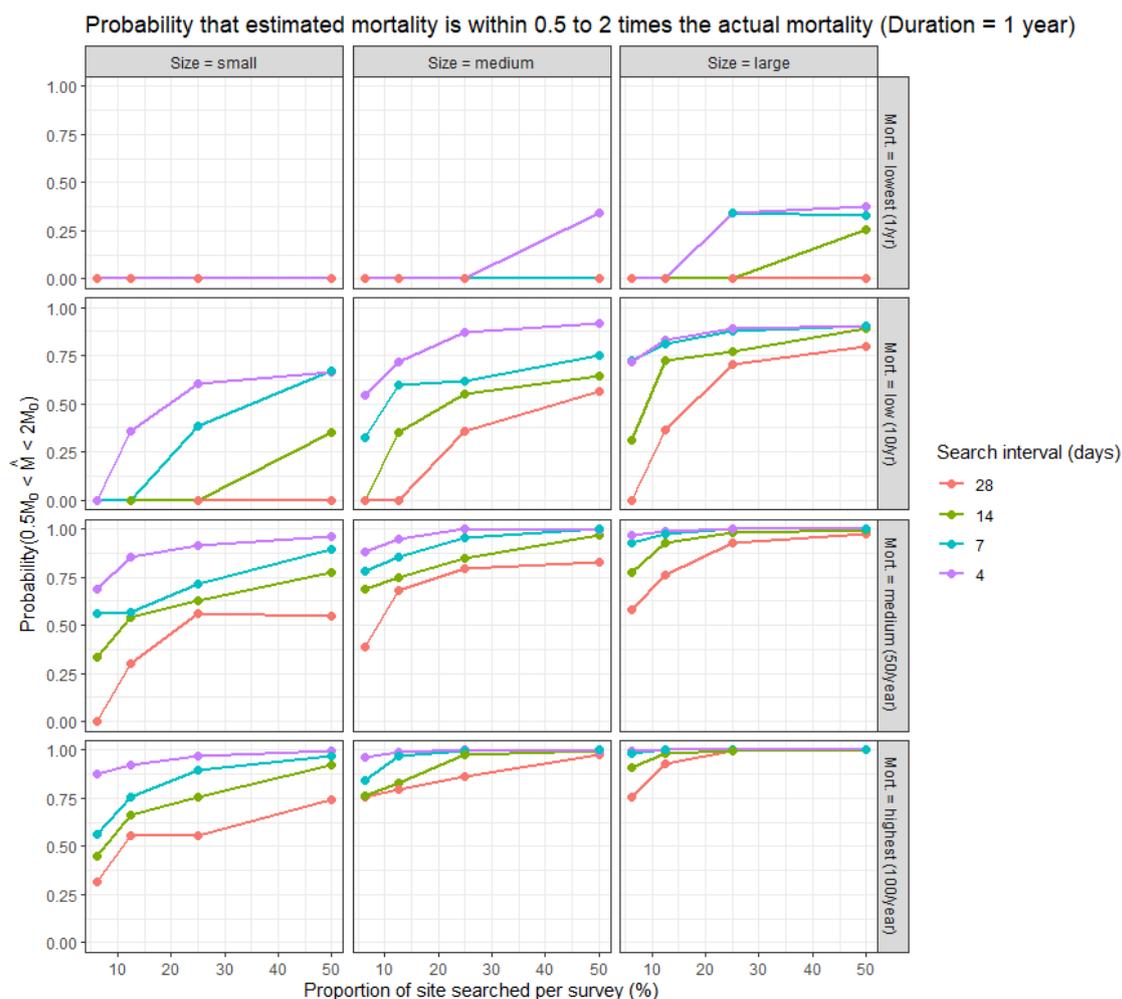
Figure 3.2: Probability that mortality estimates fall within half to double the actual mortality rate plotted according to the proportion of the site searched (coverage) and survey interval for small, medium and large sized birds across a range of annual mortality rate scenarios.

Defining a minimum standard that monitoring should have a 50% chance that mortality estimates are within half to double the true mortality rate after one year of monitoring would restrict designs to only the most comprehensive for small carcass sizes (25 to 50% coverage, surveyed every 4 to 7 days) (Table 3.3). However, this same standard could be achieved by less intensive designs for medium and large birds, particularly when mortality rates are higher. Setting a more rigid standard that monitoring should achieve an 80% chance of meeting the same target would only be attained for small and medium birds when mortality rates and sampling effort is moderate to high (detailed in Table 3.3).

Table 3.3: Monitoring designs that meet separate standards of 0.5 or 0.8 probability that estimated mortality rate will be within half to double the actual mortality rate for scenarios with low (10 birds per size class per year) and moderate (50 birds per size class per year) mortality rates for each of small, medium, and large bird carcasses.

| | | Min coverage (%) required for mortality target | | | |
| | | Low mortality | | Moderate mortality | |
Size class	Interval (d)	Pr = 0.5	Pr = 0.8	Pr = 0.5	Pr = 0.8
Small	4	25	None	25	50
	7	50	None	50	None
	14	None	None	None	None
	28	None	None	None	None
Medium	4	6.25	25	6.25	12.5
	7	12.5	None	12.5	25
	14	25	None	25	50
	28	50	None	50	None
Large	4	6.25	12.5	6.25	6.25
	7	6.25	12.5	6.25	6.25
	14	12.5	50	6.25	12.5
	28	25	None	12.5	25

Mortality estimate uncertainty

The final aspect of monitoring design performance that was evaluated was the average uncertainty of mortality estimates produced by each design. The results from this analysis displayed similar patterns to those described previously, with mortality estimates being less precise for small birds and at lower mortality rates when compared to estimates for larger sized birds under higher mortality rate scenarios (Figure 3.3). Although acceptable levels of mortality estimate uncertainty should be determined *a priori* based on population size of at-risk birds, the following summary uses a CV target of 1 to identify monitoring designs and scenarios (mortality rate, bird size) in alignment with the targets set in the previous sections evaluating alternate monitoring design metrics.

For the lowest mortality rate of 1 bird per size class per year, all of the designs performed poorly with regards to mortality estimate uncertainty (Figure 3.3), which

once again is primarily attributable to the limited chances of detecting any mortality given this mortality rate. For low mortality rates of 10 birds per size class per year, the target CV of 1 is only achieved for medium and large sized birds under the most labour-intensive monitoring designs (25 to 50% coverage, surveyed at 4 to 7 day intervals; Table 3.4). At moderate mortality rates, the target CV is met across a wider range of monitoring designs for medium and large-sized birds, but extensive sampling would still be required to achieve this goal for small birds (Table 3.4).
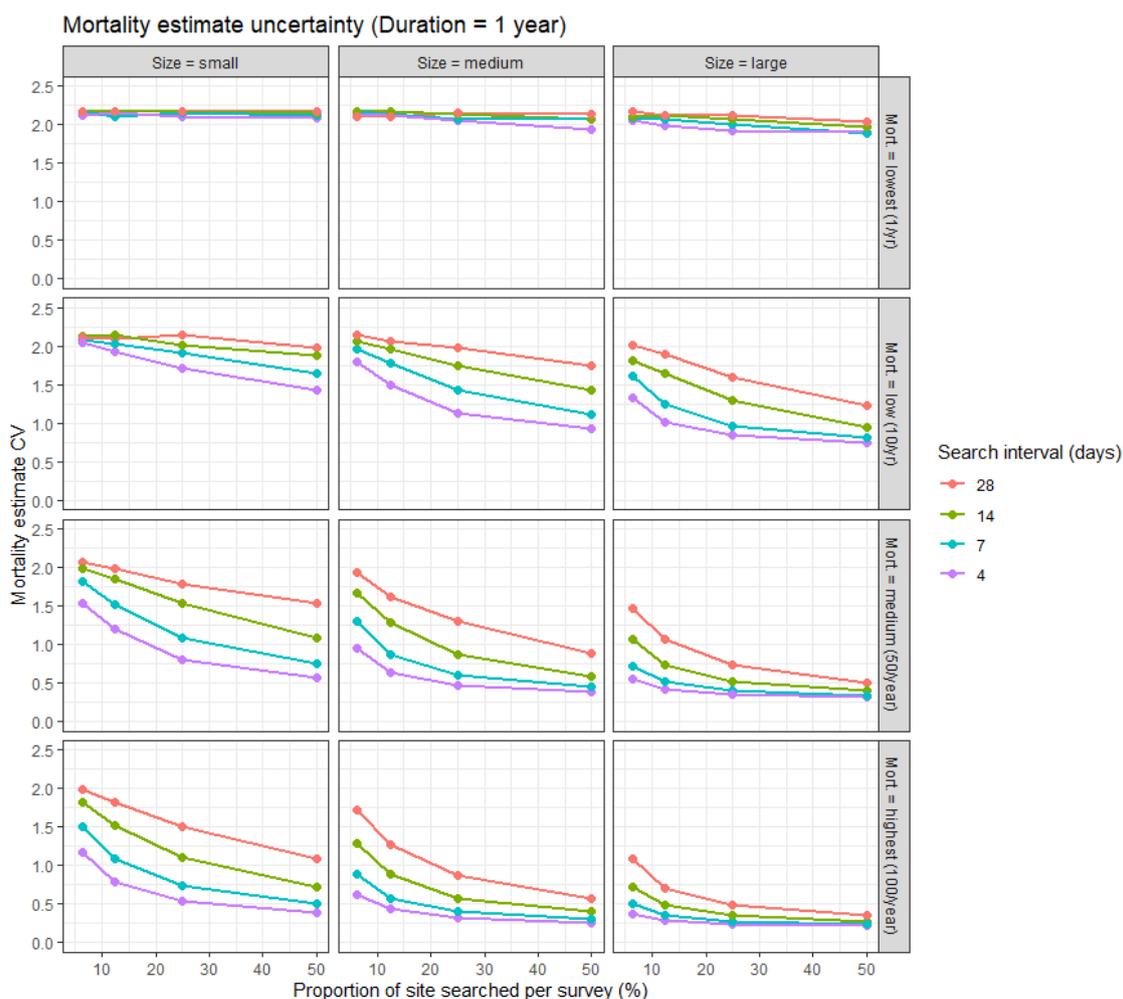

Figure 3.3: Average mortality estimate uncertainty, quantified as the coefficient of variation (CV) of annual mortality estimates, plotted according to the proportion of the site searched (coverage) and survey interval for small, medium and large sized birds across a range of annual mortality rate scenarios.

Table 3.4: Monitoring designs that meet separate standards of a coefficient of variation (CV) of one or less for scenarios with low (10 birds per size class per year) and moderate (50 birds per size class per year) mortality rates for each of small, medium, and large bird carcasses.

Size class	Interval (d)	Min coverage (%) required for CV <= 1	
		Low mortality	**Moderate mortality**
Small	4	None	25
	7	None	50
	14	None	None
	28	None	None
Medium	4	50	6.25
	7	None	12.5
	14	None	25
	28	None	50
Large	4	25	6.25
	7	25	6.25
	14	50	12.5
	28	None	25

Evaluation of sensitivity to searcher and persistence rate values

The above analyses were all based on estimates of searcher efficiency and persistence rate from studies performed outside of New Zealand. In this section, a short summary is given as to how monitoring design performance is affected given alternate assumptions of searcher efficiency and persistence rates. The following scenarios are explored for monitoring designs with surveys performed at 7-day intervals, covering 6.25%, 12.5%, or 25% of the site in each survey:

- *Basic:* This scenario is one with searcher efficiency and persistence rate set at their mid-point levels (i.e., as explored in the previous section). Unless otherwise specified, search efficiency and persistence rate were maintained at these levels in the following scenarios.
- *Low search efficiency:* Given the potential use of alternative searching methods, a lower search efficiency scenario was explored.
- *High search efficiency:* Given that vegetation appears to be currently short at the Haldon site, carcasses may be easier to find by surveyors, leading to higher

search efficiencies across all size-classes.

- *Low scavenging rate:* This scenario was explored to identify the effect that lower scavenging rates (higher carcass persistence) might have on monitoring design performance given that scavenging rate may be naturally lower at the Haldon site compared to international sites.
- *High search efficiency and low scavenging rate:* This scenario was explored to combine the potentially lower scavenging rate and higher search efficiency that may be plausible given the characteristics of the Haldon site.

Changing search efficiency and persistence had relatively large impacts on the probability of detecting mortality, particularly for small birds (Figure 3.4). For the scenarios explored (all with 7-day interval, low mortality rate), the low search efficiency scenario had the largest impact on monitoring design performance for small birds. Reducing search efficiency compared to the *Basic* scenario resulted in a drop in the probability of documenting mortality of up to 0.11, 0.06, and 0.05 for small, medium and large birds, respectively. In contrast, higher persistence rates that might be associated with fewer scavengers, resulted in the largest increase in the probability of detecting mortality for medium (0.06–0.23) and large (0.00–0.17) sized birds, but a smaller increase for small birds (0.04–0.10) when compared to the *Basic* scenario (Figure 3.4). Collectively this indicates that documentation of mortality is more limited by searcher efficiency for small birds, and by persistence rate for medium to large sized birds.

Examination of average mortality estimate accuracy (Figure 3.5) and uncertainty (Figure 3.6) displayed similar patterns across size classes and among searcher efficiency and persistence scenarios.
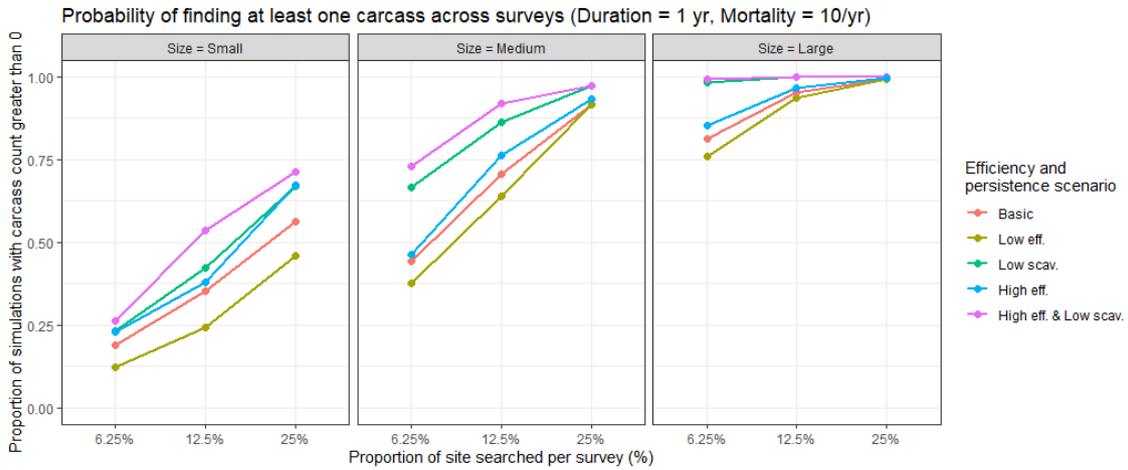
Figure 3.4: Probability of finding any carcasses plotted according to searcher efficiency and persistence scenarios for a subset of monitoring designs (7-day search interval, 6.25 – 25% coverage) with low annual mortality rates.

Figure 3.5: Probability that mortality estimates fall within half to double the actual mortality rate, plotted according to searcher efficiency and persistence scenarios for a subset of monitoring designs (7-day search interval, 6.25 – 25% coverage) with low annual mortality rates.
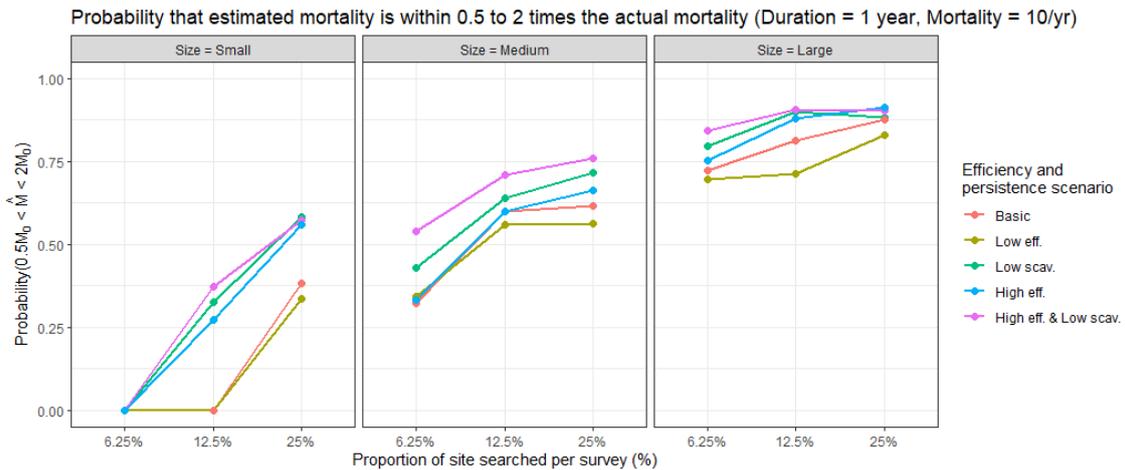
Figure 3.6: Average mortality estimate uncertainty, quantified as the coefficient of variation (CV) of annual mortality estimates, plotted according to searcher efficiency and persistence scenarios for a subset of monitoring designs (7-day search interval, 6.25 – 25% coverage) with low annual mortality rates.
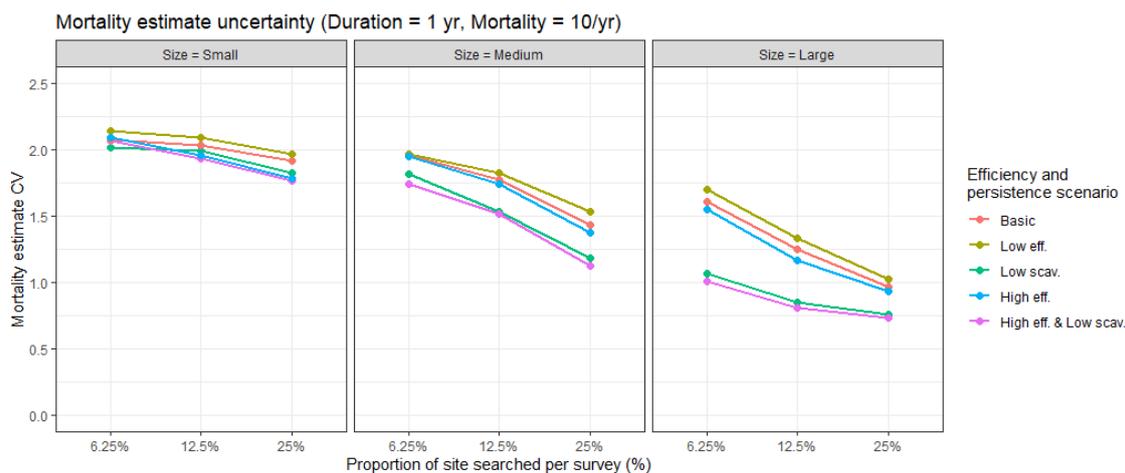
Exploration of plausible mortality rates given no carcasses observed

As a measure of false negatives (type II error), the probability of discovering no carcasses at the site, given carcasses being present, was estimated across the range of simulation scenarios (Figure 3.7). This probability declined in an exponential manner with increasing mortality rate, indicating that mortality rates above a certain value become increasingly unlikely. Additional reductions were observed with larger carcass size classes, greater site coverage, and longer survey durations. Among these factors, carcass size class exerted the strongest influence. For large carcasses, the marginal benefits of increasing site coverage or extending survey duration were comparatively small.
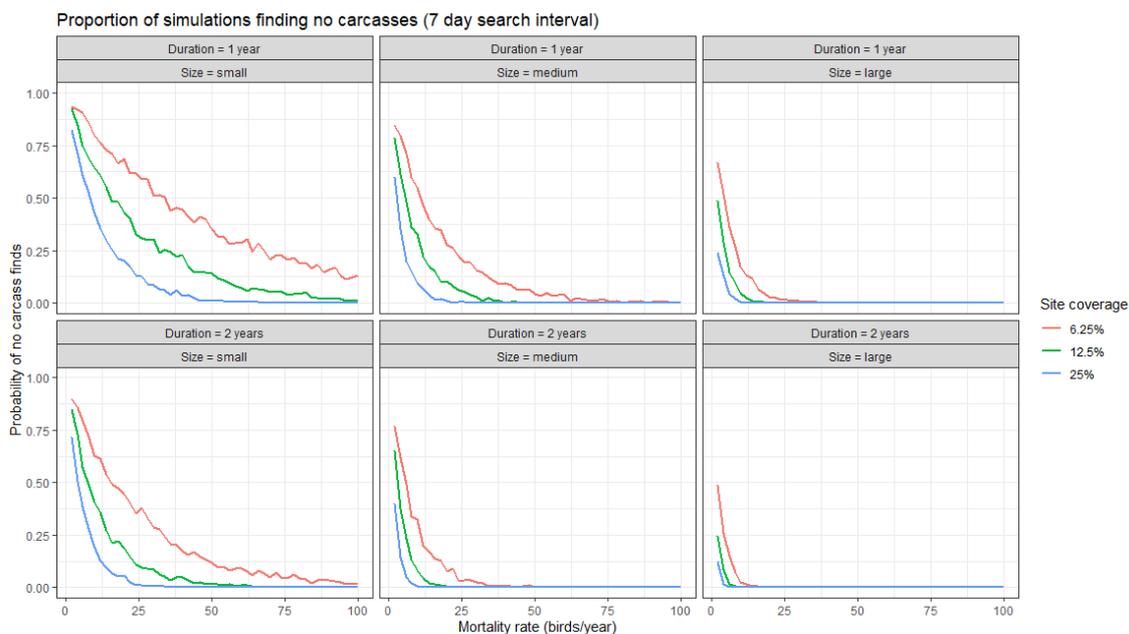
Figure 3.7: Esimated probability of observing zero carcasses in an avian mortality survey against the true mortality rate (in number of birds per year) across a number of simulation scenarios. The lines are coloured by the proportion of site surveyed and the panels are faceted by the study duration and carcass size class.

Plausible upper limits on annual mortality rate given no carcass observations were also calculated for 4, 7, and 14 day survey interval designs given the mid values for searcher efficiency and carcass persistence rates. These upper limits, which correspond to a 95% belief or confidence that the annual mortality rate is less than the stated value, range widely depending on survey effort and carcass size due to the effect of size on searcher efficiency and carcass persistence (Table 3.5). After one year of surveys, given frequent sampling (4 day search interval), upper bounds on annual mortality rate can be reduced to single figures for large birds and medium birds when surveys cover a high proportion of the site, but are considerably higher for small birds (Table 3.5). For weekly surveys, upper bounds of mortality rate for small birds are less than 50 birds per year for designs achieving 25% coverage or more, and are less than 20 and 10 birds per year for medium and large birds when surveyed weekly with a minimum of 25% coverage (Table 3.5). When surveyed bi-weekly, only the maximum coverage design meets these same levels.

Table 3.5: Upper bound of annual mortality rate (upper 95% confidence limit) given surveys document no carcasses for a range of survey designs, durations, and for alternate carcass size-classes.

Duration (yrs)	Interval (d)	Coverage (%)	Upper bound of annual mortality by size class		
			Small	Medium	Large
1	4	6.25	82	28	11
		12.5	41	15	7
		25	21	8	5
		50	12	6	4
	7	6.25	142	48	17
		12.5	72	24	10
		25	36	13	6
		50	19	8	5
	14	6.25	281	95	34
		12.5	142	48	17
		25	72	24	10
		50	36	13	6
2	4	6.25	41	14	6
		12.5	21	8	4
		25	11	4	3
		50	6	3	2
	7	6.25	72	24	9
		12.5	36	13	5
		25	18	7	3
		50	10	4	3
	14	6.25	142	48	17
		12.5	72	24	9
		25	36	13	5
		50	18	7	3

3.4.2   Searcher efficiency trials

Across scenarios, mean estimates of detection rates closely align with the simulated true detection probabilities (Figure 3.8). However, inter-iteration variability increases when fewer trials are conducted or fewer carcasses are deployed.
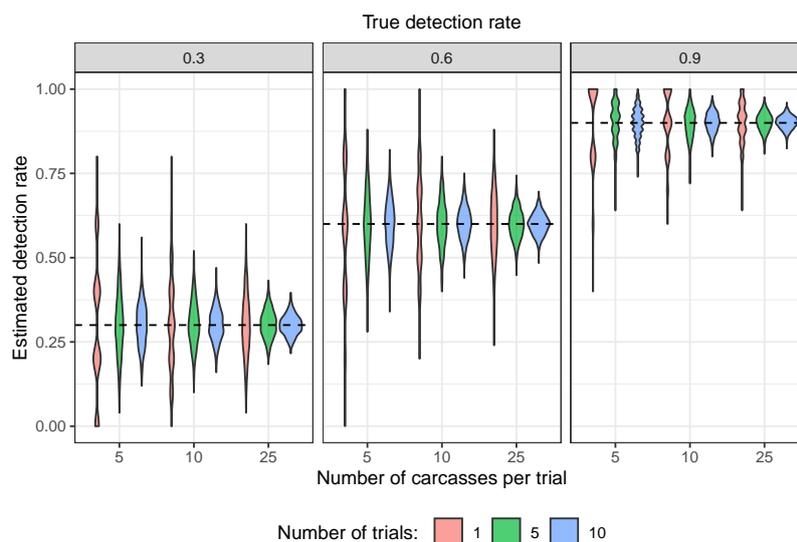

Figure 3.8: Violin plots of estimated detection rates across simulation scenarios, grouped by the number of carcasses deployed and coloured by the number of trials. Facets correspond to the simulated true detection probabilities, with dotted lines indicating the true detection rate for each scenario. The length of violins represent the range of values, while the widths reflect their relative frequency.

CV was observed to decline with both additional carcasses and more repeated trials, reflecting the expected gain in precision from larger sample sizes (Figure 3.9). Higher true detection probabilities also produce substantially lower relative variability, meaning that estimates become more reliable when detection rates are high. RMSE exhibits a similar pattern (Figure 3.10), although, the improvements at the highest true detection rate is more modest compared to the CV.
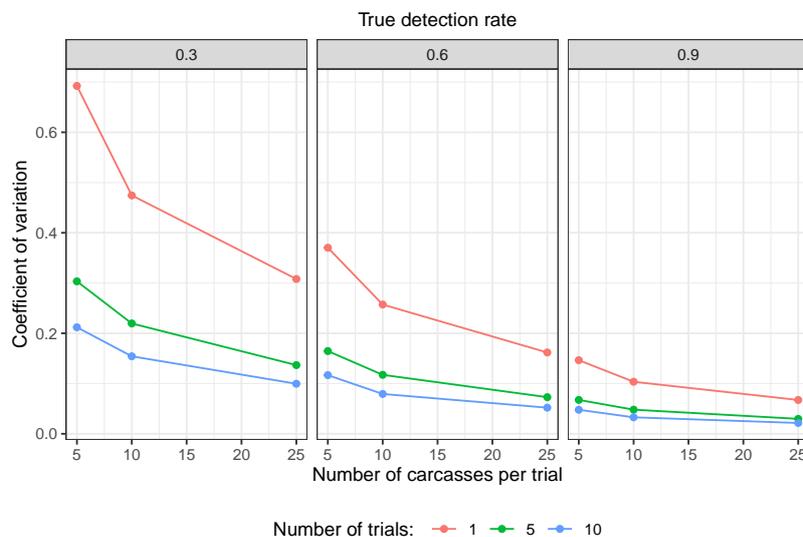
Figure 3.9: Coefficients of variation of estimated detection rates across simulation scenarios, plotted against the number of carcasses deployed and coloured by the number of trials. Facets show the simulated true detection probabilities.

Figure 3.10: Root mean squared error of estimated detection rates across simulation scenarios, plotted against the number of carcasses deployed and coloured by the number of trials. Facets show the simulated true detection probabilities.
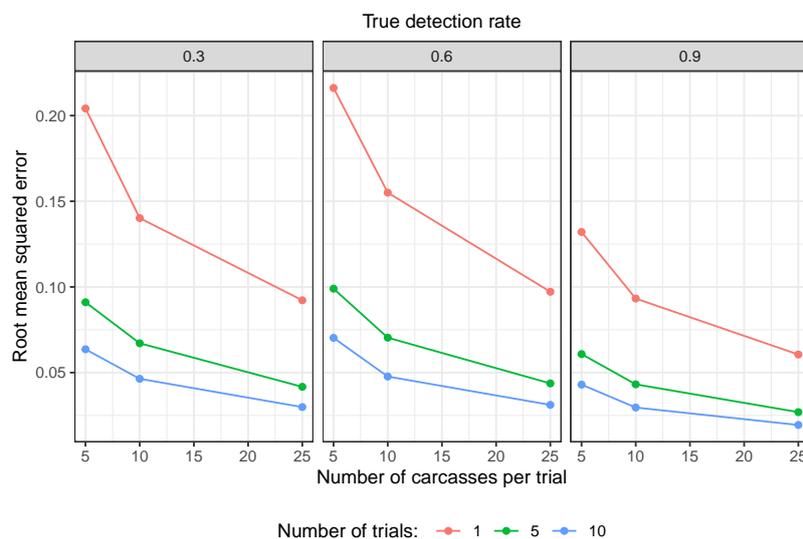
3.4.3   Carcass persistence trials

Estimated daily persistence rates were close to the simulated truth when searches were conducted daily, with precision improving as the number of carcasses increased (Figure 3.11). Longer sampling intervals (3 and 5 days) produced progressively lower estimates of daily persistence. This downward bias was most pronounced when the true persistence rate was at its lowest (0.78). The principal driver of bias appears to be the sampling interval over the number of carcasses. However, when true daily persistence was very high (0.99), both bias and variability were largely negligible across the sampling intervals and number of carcasses explored.
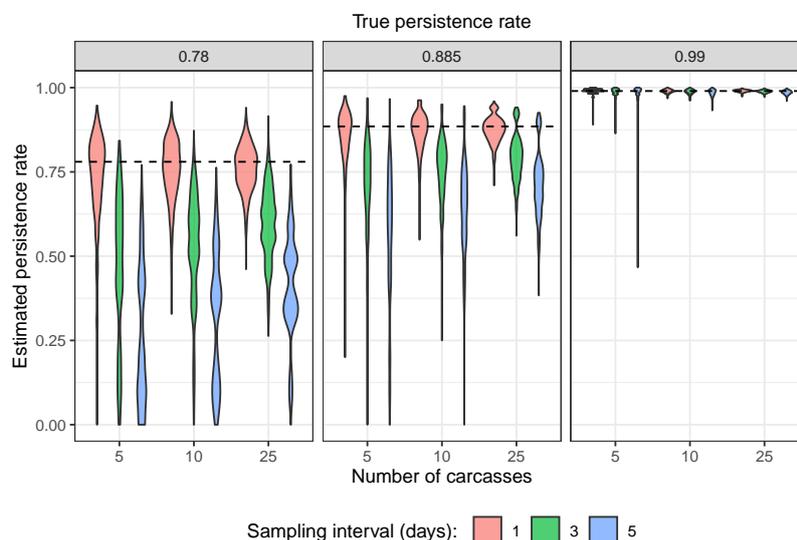

Figure 3.11: Violin plots of estimated daily persistence rates across simulation scenarios, grouped by the number of carcasses deployed and coloured by the sampling frequency in days. Facets correspond to the simulated true daily persistence probabilities, with dotted lines indicating the true daily persistence rate for each scenario. The length of violins represent the range of values, while the widths reflect their relative frequency.

Similar to the results from the searcher efficiency simulations, the CV declined with increasing numbers of carcasses and with shorter sampling intervals (Figure 3.12). The largest gains were observed when the true daily persistence probability was lowest. At very high persistence, CV were low and largely unchanged across other simulation parameters. RMSE showed a similar pattern (Figure 3.13), however, reductions were primarily driven by shorter sampling intervals than increases in carcass numbers.

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Figure 3.12: Coefficients of variation of estimated daily persistence rates across simulation scenarios, plotted against the number of carcasses deployed and coloured by the sampling frequency in days. Facets show the simulated true daily persistence probabilities.
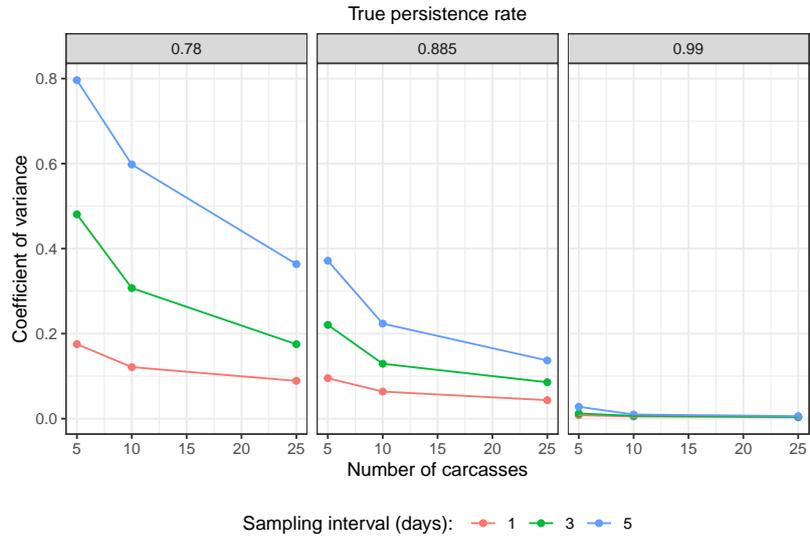

Figure 3.13: Root mean squared error of estimated daily persistence rates across simulation scenarios, plotted against the number of carcasses deployed and coloured by the sampling frequency in days. Facets show the simulated true daily persistence probabilities.
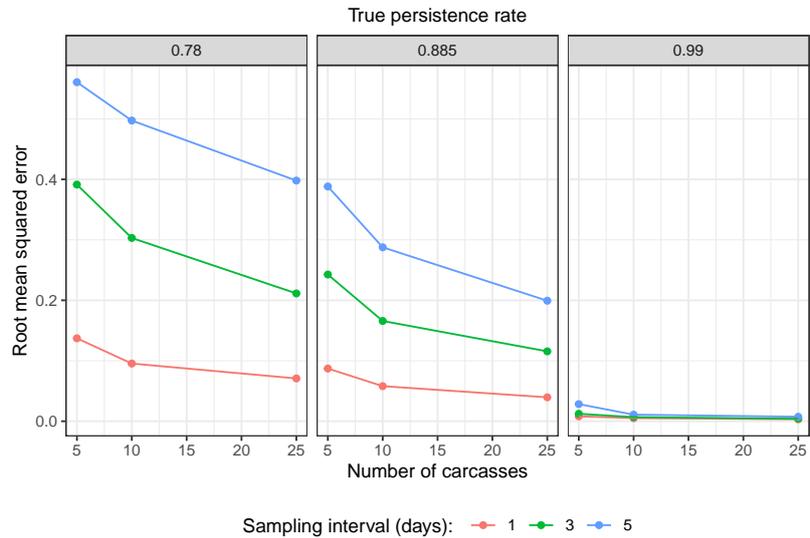
3.5   Discussion

3.5.1   Avian mortality surveys

The evaluation of monitoring design performance emphasised the need to carefully consider carcass size, when developing the monitoring program, along with the need to perform extensive monitoring (high frequency, high coverage) to detect mortality in the case when mortality rates are low. Differences in monitoring performance metrics among size-classes were frequently larger than those among alternate monitoring designs, with one design being adequate for medium and large-sized birds, but inadequate for small-sized birds. Therefore, identification of which bird sizes are of the most importance for detection will aid in developing a suitable monitoring design.

Given the above analyses and current parameterisation of search efficiency and persistence rates, monitoring designs with surveys at 28 day intervals are insufficient to meet reasonable targets of mortality documentation and estimate reliability. Monitoring designs performing surveys at 7-day intervals are sufficient when applied at relatively high coverage (12.5 to 50%), but still may not capture mortality of small birds. However, monitoring designs that perform adequately for small birds according to the same targets may be impracticable, requiring extensive and frequent searches that may be costly and time consuming. Emerging technologies in the form of drone surveys may be practical for implementing high frequency, high coverage surveys, but there is little to no information on search efficiencies that could be attained using this observation platform within a solar farm context to test their efficacy.

The exploration of alternate searcher efficiency and persistence rates identified that documentation of any mortality is most limited by searcher efficiency for small birds, and by carcass persistence for medium to large birds. Therefore, if the aim of monitoring were to detect mortality of small-sized birds, then increasing search efficiency by having more searchers or teams with trained search dogs may be advantageous. This also suggests that any changes in scavenger community following the construction of the facility are likely to result in changes in the ability of any monitoring design to document mortality.

Finally, the exploration of mortality rates given no carcass finds suggests that mortality

rates of up to 100 birds per year are still plausible for small birds when surveyed with the lower effort designs. However, given observations of no medium and large sized birds, plausible estimates for annual mortality rate are reduced considerably (< 20 birds per year), due to their higher persistence and searcher efficiencies. Monitoring over longer periods also reduces the plausible range of mortality given no observations, as the weight of evidence increasingly points towards a genuinely low mortality rate.

It should be noted that these analyses were based on searcher efficiency and carcass persistence rates from locations outside of New Zealand (predominantly energy infrastructure projects, including solar farms in the USA and South Africa), that may not be representative of the Haldon site. It is plausible that searcher efficiencies and carcass persistence rates will be higher at Haldon, given the limited vegetation to obscure carcass finds, and lower scavenging rates due to fewer mammalian, or other, scavengers. In the event that searcher efficiencies and carcass persistence rates are higher than those specified in simulations, then any given monitoring design will perform better in terms of probability of mortality detection and with regards to the reliability and precision of annual mortality estimates. Furthermore, with higher search efficiencies and carcass persistence rates, the plausible upper bounds for annual mortality rate given the observation of zero carcass finds will be closer to zero, providing additional confidence that mortality rates are genuinely low, rather than an artefact of survey design. As the size-classes simply represent alternate values for searcher efficiency and carcass persistence rate (small = low efficiency & low persistence, medium = mid efficiency & mid persistence, large = high efficiency & high persistence), then monitoring design performance can be drawn from the searcher efficiency and persistence scenario results that best matches the realised rates at the Haldon site.

However, without reliable quantitative values for searcher efficiency and carcass persistence rates at Haldon, including how they vary among size-classes and observer type, it is difficult to foresee how well any monitoring design will perform once implemented. Therefore, it would be advisable to rerun these analyses with updated searcher efficiency and persistence rates resulting from the trials detailed herein to provide better measures of monitoring performance.

3.5.2   Searcher efficiency trials

In the searcher efficiency simulations, precision and accuracy declined when either the number of trials or carcasses was reduced, as indicated by increases in the coefficients of variance and root mean squared error respectively. Higher true detection probabilities consistently produced lower relative variability, suggesting that estimating detection rates is easier when detection probability is high.

3.5.3   Carcass persistence trials

The carcass persistence simulations showed a similar pattern. Precision and accuracy generally declined when the sampling frequency decreased or the number of carcasses was reduced. However, as search intervals increased to 3 or 5 days, the daily persistence estimates became increasingly biased downward, particularly at lower true persistence levels (e.g. $p = 0.78$). Sampling interval appears to be the primary determinant of accuracy, whereas the number of carcasses mainly influences precision. At very high true persistence ($p = 0.99$), both bias and variance were small across all scenarios, meaning that when carcasses persist for a long time, the influence of study design becomes less consequential.

3.6   Recommendations

3.6.1   Avian mortality surveys

Recommendation: Conduct surveys at weekly intervals, or bi-weekly at a minimum coupled with high coverage.

Rationale: More frequent searches performed better at both documenting mortality, given it occurs, and producing reliable estimates of annual mortality rate. Survey intervals longer than 14 days performed poorly, particularly for smaller carcasses. Shorter survey intervals are also more likely to detect mortality shortly after it has occurred, such that carcass condition may be better, thus making it easier to diagnose species identity. The reporting of species identity may be paramount when reporting mortalities at the site to concerned parties. Survey intervals shorter than 7 days (i.e., 4 days) perform better, but may be impractical for human searchers given the continued workload required. However, they may be logistically feasible when coupled with alternate search agents, such as drones.

Recommendation: Attempt to achieve a minimum of 12.5% coverage per survey.

Rationale: Surveying a higher proportion of the site during each survey gives a better chance of documenting any mortality that may have occurred in the intervening time since the last survey. Mortality rate estimates were also more reliable and precise for designs with higher coverage, but these may only be logistically feasible with some form of automated searchers (i.e., drones). Coverage in the range of 12.5% to 25% of the site in each survey struck a good balance between returning reasonable chances of detecting mortality, and providing reliable estimates of annual mortality rate, whilst also being practical. However, it should be noted that coverage and survey interval are interconnected, in that if lower coverage is more logistically feasible than higher coverage designs depending on the availability of surveyors (i.e., it is possible to do in one day, as compared to over several days), then this should be paired with more frequent surveys, and vice-versa.

Recommendation: Record size, or size-class, for any found carcasses.

Rationale: Monitoring design performance was highly dependent on carcass size, or more specifically the combination of searcher efficiency and carcass persistence rate, across all monitoring scenarios and mortality rates. Furthermore, given a set of carcass counts following monitoring, producing mortality estimates is highly dependent on the assumed, or estimated searcher efficiency and carcass persistence rates, which are known to vary considerably with bird size. Without knowledge of the approximate sizes for any carcass finds there is a high chance that mortality estimates may over- or under-estimate the true mortality rate. Recorded size-classes should match those used in search efficiency and carcass persistence trials performed at the site to be most reliable when estimating annual mortality rate. The collection of additional information from each carcass, including the taking of photographs and recording morphometric measurements (i.e., bill or wing length), where available, may aid the identification of bird size and identity, particularly for carcasses that are highly scavenged.

Recommendation: As much as possible, maximise search efficiency and carcass persistence rate.

Rationale: Search efficiency appeared to be the main limiting factor in documenting mortality for small birds, the probabilities of which were low for many of the monitoring designs when sitewide mortality rates are low. This was less of a concern for medium to large-sized birds, but any increase in search efficiency for small birds would return greater chances of documenting mortality. Whilst mortality estimates were more sensitive to persistence rates for medium to large-sized birds, controlling the rate of carcass degradation and scavenging across all sources may be beyond the control of project managers. However, having higher search efficiency and rates of carcass persistence vastly improves the probability of detecting mortality and the accuracy and precision of resultant mortality estimates, including the reduction of upper mortality estimate bounds when no carcasses are observed. Therefore, pursuing means to maximise search efficiency and rates of carcass persistence will benefit monitoring design efficacy.

Recommendation: Review monitoring protocol annually in light of ongoing changes to site characteristics that may influence searcher efficiency or carcass persistence rates.

Rationale: As noted in the previous recommendations, monitoring design efficacy and estimation of mortality are both highly dependent on rates of searcher efficiency and carcass persistence rates. Given that the site is likely to undergo ongoing changes to both flora and fauna occupying the site following the deployment of solar panels, these changes will likely influence how effective monitoring designs are. Annual or biennial reviews of the monitoring protocol, including checks on searcher efficiency and carcass persistence rates, would ensure that monitoring remains fit for purpose in light of ongoing changes to site characteristics.

Recommendation: If, or when, reporting zero carcass finds, attempt to accompany this with an appraisal of plausible mortality rates given no finds.

Rationale: Monitoring simulations suggested that observations of no carcass finds were probable across a range of alternate monitoring designs and bird sizes when annual mortality rates were low. However, given the observation of no carcasses, a plausible range of annual mortality can still be presented via either simulations (as employed here) or via alternative statistical techniques. Given no carcass detections, the presentation of an upper bound on mortality rate may help to reassure concerned parties on the potential impacts of the facility on local bird life.

3.6.2   Searcher efficiency trials

Recommendation: Conduct more repeated trials with fewer carcasses

Rationale: Both precision and accuracy improve substantially with additional carcasses and more repeated trials. However, using too many carcasses at once risks signalling to searchers that they are participating in a trial, which may inadvertently alter their behaviour. For example, they may search more thoroughly than they normally would, which would artificially inflate observed detection rates. For this reason, conducting more trials with fewer carcasses per trial is preferable. This approach is also supported by the simulation results, which showed that repeated trials improved precision and accuracy more efficiently than simply increasing the number of carcasses in a single trial. However, this issue may be irrelevant when drones are used as search agents.

Recommendation: Adjust sampling intensity based on expected detection probability.

Rationale: When detection probability is high, the simulations show that both precision and accuracy remain high even with modest sample sizes. This means that study effort can be allocated more flexibly in high detection environments. However, when detection is expected to be low, such as in dense vegetation or near complex artificial structures, additional trials and/or more carcasses are required to achieve comparable precision and accuracy.

3.6.3 Carcass persistence trials

Recommendation: Implement a higher sampling frequency with fewer carcasses

Rationale: Increasing carcass numbers improved precision and accuracy, though it did not correct for bias caused by long search intervals. Intervals of 3–5 days created substantial negative bias in daily persistence estimates, particularly when true persistence was moderate (which could be expected for smaller species). If sampling effort is restrictive, monitoring could be tailored to be intensive during the first few days after carcass placement, where most losses are expected to occur, and then gradually extend the sampling interval later into the study period. Using fewer carcasses per deployment is also more representative of natural carcass availability and helps avoid overwhelming the local scavenger community.

Recommendation: Adjust sampling intensity based on expected persistence probability

Rationale: When persistence is high, the simulations show that both precision and accuracy remain high even with modest sample sizes. However, when persistence is expected to be low, such as in locations with high scavenger densities or rapid decomposition, more frequent searches and/or more carcasses are required to achieve comparable precision and accuracy. This may be relevant if you expect the scavenging community to change through time with the construction of fencing or predator control at the site.

Recommendation: Consider camera traps if scavenger identity or behavioural dynamics are of interest.

Rationale: Camera traps allow continuous monitoring of carcasses and can be programmed to take photos at a regular intervals to more accurately estimate time to removal. Motion triggers also allow for the identification of scavenging species and detailed observations of their interactions of the carcass. These data can be particularly valuable in determining whether, and how, the scavenging community changes in reponse to management action such as fencing or predator control. The primary trade-off is the initial cost of the devices and the increased post-processing effort.

3.6.4   Next steps

Recommendation: Implement search efficiency and carcass persistence trials pre-construction.

Rationale: Accurate estimates of detection probabilities and carcass persistence rates are critical to obtaining reliable estimates of avian mortalities, with high confidence. Given the context-dependent nature of searcher efficiency and carcass persistence, values obtained from facilities outside of New Zealand and unlikely to be appropriate for the Haldon site. Having *in-situ* estimates of these factors will enable the avian mortality monitoring design advice to be refined and tailored for the Haldon site. These trials will also enable alternative search agents (e.g., humans and drones) to be tested, compared and evaluated for cost effectiveness.

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5. Appendix

5.1   Avian mortality survey simulation routine

Avian mortality survey simulations were performed by simulating the separate processes of (i) mortality occurrence, (ii) carcass persistence and loss given initial mortality, and (iii) carcass finds given surveys of specific areas. Simulation state was updated on a daily schedule, updating the number of carcasses across the site, followed by updating the state of each carcass, simulating carcass losses via scavenging, and finally carcass finds if a survey happened on a particular day. Each simulation was performed for a total of five years (1825 days) as it was anticipated that initial monitoring and reporting may be desired over this timeframe. It also allowed for simulation of reporting carcass finds, and mortality rate estimation after one, two, and five years of monitoring, allowing for assessment of monitoring performance according to duration.

5.1.1   Simulation routine

On each simulated day, new mortalities were simulated to occur according to a poisson point process, whereby a number of carcasses, n, were generated according to a Poisson distribution with a rate, λ, equal to the annual mortality rate, M, expressed at a daily level.

Each simulated carcass was then assigned a location, generated at random from a uniform distribution in both x and y directions, mimicking equal mortality rate across the site. In addition to location, each carcass was assigned a size-class as one of small, medium, or large at random, with equal probabilities among size-classes.

Initially, carcass fate was set to *"present"*, indicating that the carcass was available to be found if a survey occurred on that day covering the area where the carcass resided. On each subsequent day, carcass fate for all carcasses still *"present"* was updated to either *"present"*, indicating a carcass remained available for detection on that day, or *"lost"*, with a probability of remaining *"present"* equal to the daily persistence rate for the carcass size class. This was achieved via generation of a Bernoulli random variable (0 = loss, 1 = remains), with probability ρ_s, where s denotes size-class (loss simulated via a binomial random draw). Performing this each day implies that the proportion of carcasses remaining after d days declines as $\rho_s{}^d$. While this is a strong assumption regarding carcass persistence, we have little other data to support more complex functional forms.

Surveys were performed on particular days, separated by a set interval of I days. The simulated site was divided into 32 equally sized blocks (as described in Section 3), such that each block could be thought of as a 10 ha area within the Haldon facility. During each survey, a subset of blocks are "searched" and a count recorded for each size-class for the entire block in that survey. The survey design was established so that blocks are surveyed systematically, such that if 12.5% coverage was desired per survey (4/32 blocks), then survey 1 would involve searching each of blocks 1-4, followed by blocks 5-8 in survey 2, and so forth. During actual monitoring, blocks searched within each survey ought to be distributed throughout the site, but for this simulation, where mortalities are evenly distributed throughout the site, the two approaches are functionally equivalent.

Within each survey, the search process was simulated by first identifying those carcasses that were still *"present"* on the survey date within the searched area, and noting it's size. For each carcass present, whether it was found or not was simulated by generating a Bernoulli random variable (0 = not found, 1 = found) with probability equal to the search efficiency, θ_s, specific to the carcass size-class. The fate of any found carcasses was then updated to *"found"*, which removes them from being available in subsequent searches, mimicking carcass collection by surveyors (unfound carcasses remained as *"present"*. Following simulation of the search process, the total number of carcasses found in a particular block was recorded. This resulted in a survey dataset, which included survey occasion and a single count of the total number of found carcasses per block searched during each survey. This served as the data that was analysed to evaluate monitoring design performance for each simulation.

5.1.2   Simulation variables

The simulation depends on a range of variables including those associated with survey design (site coverage, survey interval), to mortality rate and carcass characteristics (searcher efficiency, carcass persistence rate). For each variable a range of values was identified based on known rates and recommendations for monitoring of solar farms from existing studies. The values chosen for each variable are given in Table 5.1.

Table 5.1: Variables included in monitoring design evaluations.

Variable	Description	Size class	Values	Units
Coverage	Proportion of site searched in each survey		6.25, 12.5, 25, 50	%
Interval	Interval between surveys		4, 7, 14, 28	days
Mortality rate	Mortality rate for each size class for the entire facility		1, 10, 50, 100	birds/year
Search efficiency	Probability of finding a carcass given it is present in the survey area	Small	30, 40, 50	%
		Medium	60, 70, 80	%
		Large	70, 80, 90	%
Persistence rate	Probability that a carcass persists from one day to the next	Small	78, 87, 83	%
		Medium	86, 90, 94	%
		Large	92, 96, 99	%

For each variable we chose low, middle, and high values, where the middle values was informed by previous studies. - *Coverage:* 20-30% cited as a good level of coverage in the literature

- *Survey interval:* 7 to 28 days have been performed at solar farms in the USA
- *Annual mortality rate:* little is known about mortalities on solar farms in New Zealand, but the expectation is that mortality rates will be lower than those where monitoring has been performed in the USA. Lowest annual mortality rates from solar farms in California (Desert sunlight) are equivalent to 0.54 birds/ha/year, which when scaled to Haldon (320 ha) gives an annual mortality rate of 174. We therefore chose the middle value to reflect 50 birds per size class

(150 total), and higher and lower values to provide comparisons under low and high mortality scenarios.

- *Searcher efficiencies:* These were selected based on a review of search efficiencies and carcass persistence rates at energy infrastructure facilities (Barrientos REF). We selected search efficiencies representative of a 20-30 g bird (small), 300-400 g bird (medium) and 1100 g bird (large) for the mid points, and then selected values that were 0.1 higher or lower than this.

- *Carcass persistence rates:* These were selected based on a review of search efficiencies and carcass persistence rates at energy infrastructure facilities (Barrientos REF). As for search efficiency, we selected daily persistence rates at relevant sizes per size-class for the middle level value, and then included low and high scenarios by calculating the daily persistence rates that would result in 0.1 difference in persistence after 3 days.

Simulations were performed for every possible permutation of the values presented in the table above, which we label as separate scenarios. For each scenario, a total of 500 simulations were performed to evaluate different possible outcomes from each.

5.1.3 Mortality estimation and monitoring design performance

For each simulation, the carcass counts were analysed to produce an estimate of mortality, and whether any carcasses were documented by the given design throughout the duration (1, 2, and 5 years of monitoring) of monitoring, specific to each size-class of carcass. It was necessary to do this per size-class given differences in searcher efficiency and persistence of different body sizes.

Mortality was estimated by first estimating the daily mortality rate at the block level from the observed counts, given information on searcher efficiency and carcass persistence rates. It is assumed that daily mortality rate at the block level, λ_s, is constant through time and among survey blocks.

Given an effective search interval of I, the number of carcasses potentially available to be found per survey is the sum of daily mortality rate at the block level, λ_s, offset by the proportion of carcasses that remain from when they first appear to the survey date.

$$N_s = \sum_{j=0}^{I-1} \lambda_s \rho_s^j$$

However, as carcasses may be missed in a previous survey, it is also necessary to account for those carcasses that remain present to the current survey and available to be found. Assuming that carcasses only remain for a maximum of three survey intervals expands the above relationship to

$$N_s = \lambda_s \left[\sum_{j=0}^{I-1} \rho_s^j + (1 - \theta_s) \sum_{j=0}^{I-1} \rho_s^{j+I} + (1 - \theta_s)^2 \sum_{j=0}^{I-1} \rho_s^{j+2I} \right]$$

If searcher efficiency and persistence rates are constant, then the above relationship simplifies to a constant multiplied by the daily mortality rate.

$$N_s = \lambda_s \beta_s$$

where, β_s, includes all of the information relating to loss of carcasses and missed detections in previous surveys.

Given that, the expected count per survey of a given block is the number of carcasses potentially available multiplied by the detection rate, θ_s, specific to the carcass size-class.

$$\hat{C}_s = \theta_s \lambda_s \beta_s$$

which can be rearranged to give an estimate of the daily mortality rate

$$\lambda_s = \frac{\hat{C}_s}{\theta_s \beta_s}$$

Given this relationship, an estimate of daily mortality rate for each size-class, λ_s, was estimated by first calculating the expected count per search, $\hat{C}_s$, from the count data. An estimate for $\hat{C}_s$, and it's 95% confidence interval, was produced by fitting a Generalised Linear Model to the counts for each size class, where counts were assumed

to follow a Poisson distribution. Given an estimate for daily mortality rate per block, $\hat{\lambda}_s$, the annual mortality estimate, $\hat{M}_s$ can then be calculated by multiplying by the total number of blocks in the site, N_B, and by 365 to go from daily to yearly mortality

$$M_s = 365\lambda_s N_B$$

Estimates of $\hat{M}_s$, along with their 95% confidence interval, were estimated for each simulation.

5.2 Upper bounds on annual mortality rate given observations of no carcasses

In the final part of the avian monitoring simulation results, values are provided for the upper bound of annual mortality rate given no observations of carcasses across surveys for a subset of designs. Given a series of n observations of 0 carcasses on surveyed blocks, an upper bound on annual mortality can be constructed by examining the likelihood of those observations given some underlying rate, λ_c for the expected carcass count per block per survey. This can be related to annual mortality rate by accounting for missed detections and losses as detailed in the mortality estimation section above.

Assuming that counts are distributed according to a Poisson distribution, the collective likelihood of n observations of zero is given as

$$L(\mathbf{x} = \mathbf{0}|\lambda_c) = \prod_{i=1}^{n} e^{-\lambda_c}$$

as the probability density function of the Poisson distribution simplifies to $e^{-\lambda}$ when counts are equal to zero. This equation then simplifies to

$$L(\mathbf{x} = \mathbf{0}|\lambda_c) = e^{-n\lambda_c}$$

Assuming no prior knowledge of λ_c, equivalent to a uniform prior distribution, then the above relationship can be reformulated in terms of the posterior distribution of λ_c given the series of n counts of 0 carcasses:

$$P(\lambda_c | \mathbf{x} = \mathbf{0}) \propto e^{-n\lambda_c}$$

The posterior distribution can be thought of as describing the relative likelihood of alternate values for λ_c that may give rise to observations of no carcasses. As this is a negative exponential function (as illustrated in the Results section from simulations), then the relative likelihood of higher values for λ_c become diminishingly small as λ_c increases. This is intuitive because a higher expected rate of carcasses should be deemed less likely given a series of observations of 0 carcasses, but relatively lower rates may still be plausible and therefore have a higher probability of being true. Furthermore, the steepness of this decline is determined by the sample size, n, with steeper rates as n increases. This is also intuitive, as you would expect greater confidence in lower mortality rates as your sample size of 0 counts increases, but relatively lower confidence with smaller sample sizes.

Finding some upper bound for the expected count rate, λ_c, involves identifying the value for λ_c where the summed probability over lower values equals some predetermined level of confidence or credibility. Defining this probability level as 0.95 equates to identifying the value for λ_c where one can have 95% faith that the expected count rate is lower than this value. The value for this upper bound, labelled as λ_c^u, can be found by taking the definite integral of the posterior function from 0 to λ_c^u and dividing by the integral from 0 to ∞ (i.e., all possible values; for standardisation) and setting the result equal to 0.95. The definite integral of $e^{-n\lambda_c}$ from 0 to some upper bound q is given by

$$\int_0^q e^{-n\lambda_c} \, d\lambda_c = \left[-\frac{1}{n} e^{-n\lambda_c} \right]_0^q$$

Evaluating this from 0 to λ_c^u and dividing by the integral from 0 to ∞ and setting the result to 0.95 gives

$$1 - e^{-n\lambda_c^u} = 0.95$$

This can then be rearranged to find the upper bound on the expected count rate, λ_c^u, that corresponds to 0.95 probability given an observation of n counts of zero carcasses.

Following that, an upper bound on annual mortality rate can be calculated from this by converting the upper bound for expected count rate to an annual mortality rate accounting for survey interval, coverage, carcass loss and missed detections, as detailed in the previous section.