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Process-based vs. ad-hoc methods to estimate mortality using carcass surveys data: A review and a note about evidence complacency

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ABSTRACT

To quantify the rate at which wildlife die from anthropogenic sources like wind farms and poisoning, one may look for the carcasses. The number of detected carcasses, or the absence of carcasses, however needs to be corrected for imperfect detection and early removal by scavengers. To perform this correction, there exist more than a dozen “open” variants of the Lincoln-Petersen “closed-population” capture-recapture estimator. These different variants typically yield very different results because they are based on different assumptions that end users do not always consider. I conduct a simulation study highlighting severe biases in Lincoln-Petersen type estimators when their assumptions are violated. Recent attempts to relax these assumptions within the closed-population capture-recapture paradigm involve increasingly complex analysis, yet the resulting modified estimators still apply to restricted settings only. By contrast, there is an abundant literature about flexible, process-based, open-population capture-recapture models and how to fit them to survey data using numerical likelihood optimization. My simulations illustrate the good performance of this approach, in the presence of complex sources of bias, for moderate sample sizes. I review existing guidelines to deal with sparser datasets. As a perspective, I use the example of bird mortality estimation in wind farms to argue that the lack of methodological consensus can set the stage for evidence complacency. Biostatisticians should strive to avoid the proliferation of alternative methods and instead work towards increasingly general and unified frameworks.

1. Introduction

Energy suppliers increasingly turn to wind energy as a way to curb carbon dioxide emission. However, whether the low carbon dioxide emission always and everywhere justifies the environmental impact of wind energy is still debated, partly because we lack adequate data and methodologies to address imperfections in available data (Devine-Wright, 2005; Kunz et al., 2007; Loss et al., 2014). For example, in France, less than 5% of the impact assessments conducted in the last 20 years followed a full, before-after control impact protocol (Marx, 2017). As a result, these reports give a partial view of the impacts and are difficult to compare to each other.

One of the major environmental impacts of wind energy is collisions of flying wildlife, including protected species, with wind turbines (Arnett et al., 2016; Erickson et al., 2014; Loss et al., 2014; Table 1). Wind farm operators are typically required to perform standardized carcass surveys. The data resulting from these surveys need to be corrected for variation in nuisance parameters: imperfect detection of carcasses, and early removal by scavengers. More than a dozen methods are currently available to perform this correction.

I first review the principles of the different methods, their underlying assumptions about the processes at stake, and their range of application. Second, I conduct a simulation study to compare the performance of different methods in a range of scenarios. Third, I discuss the managerial implications of the proliferation of methods, invoking recent debates about evidence complacency.

2. Material and methods

2.1. Schematic overview: a process-based model of carcass surveys

In most cases, field technicians conduct a series of systematic surveys separated by unmonitored intervals between surveys. The problem at hand can then be reformulated into an open-population capture-recapture problem (Cormack, 1964; Jolly, 1965; Seber, 1965), i.e., a hierarchical, hidden Markov chain model with an observation process (detection during the sampling occasions) and a state process (entry of new carcasses and disappearance of old ones during the intervals between sampling occasions) (Fig. 1).

The main difference with usual capture-recapture problems is that carcasses cannot be ‘released’ back into the population, first, because they are motionless, and second because in many cases the field

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Table 1
Non exhaustive overview of various methods for pre-construction surveys of populations at risk.

Objective	Methods
Rapid assessment	Desktop-based synthesis of habitats and species of conservation concern. Collation of available distribution and population size information.
Initial abundance of species of conservation concern; and population trend over years	Ground- or aircraft-based distance sampling, Capture-mark-recapture, other types of population surveys
Rate at which species use the project area	Point counts documenting time spent by individuals over project area (cf. "eagle.minutes"). GPS tracking and home range analysis. Radar surveys. Nest searches.
Vulnerability to collision when on site	GPS tracking or visual records of flight height
Environmental proxies for vulnerability	Weather patterns (e.g., cloudy conditions influence collision rate by night-migrating passerines, presence and speed of thermal convection cells influence collision risk by soaring birds, …). Concentrations of prey and other resources. Landscape features such as slopes used by soaring raptors for orographic uplift.

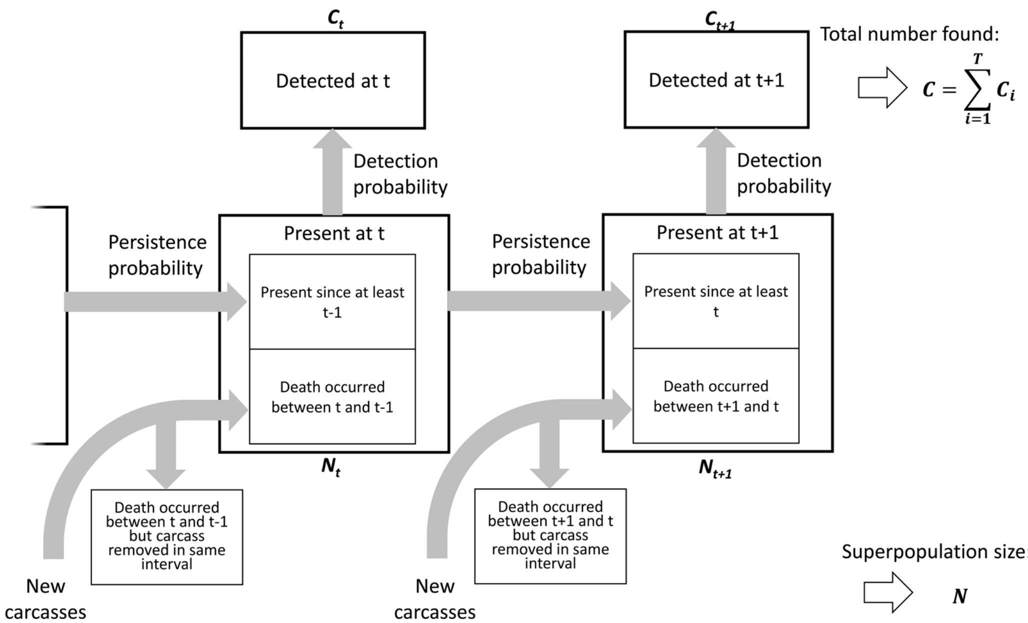

Fig. 1. Schematic representation of the hierarchical and open-population nature of the problem at hand, explaining why the number of detected carcasses is lower than the total number of fatalities, but also that carcasses may persist undetected for some time. Carcasses can only be detected once, but they can be left in place upon detection to serve in detection and persistence trial experiments.

technicians are required to remove the carcasses upon detection. For this reason, trial experiments are conducted in addition to the carcass searches. "Detection trial experiments" consist in planting carcasses or surrogate carcasses at locations unknown to the field technicians and letting them record whether they detect them. "Persistence trial experiments" consist in monitoring the fate of planted carcasses and recording how long they persist.

2.2. Variations around the Lincoln–Petersen estimator

Noting N_t the instantaneous population size (number of carcasses on the ground at any point in time) and neglecting the time required to systematically search the area for carcasses, the Lincoln-Petersen estimator (Williams et al., 2002) is $\hat{N}_t = C/\hat{p}$, where C is the number of individual carcasses detected, and p is the probability to detect a carcass. In basic capture-recapture applications, p is estimated by drawing K individuals, marking and releasing them in the population, and eventually drawing another sample, of which k will be marked. The estimator for p is then $\hat{p} = k/K$. In applications to carcass search data, p is estimated using the detection trial experiment as described in the previous section.

The Lincoln-Petersen estimator provides a snapshot of the instantaneous population size. However, managers have little interest in the instantaneous population size because of the open-population nature of the problem. At any given time, some of the carcasses currently in the population may be too old (therefore not relevant to the time period of interest), while some of the carcasses may have disappeared already (Fig. 1). In an open capture-recapture problem, the parameter of interest is indeed the size of the "superpopulation" (*sensu* Schwarz and Arnason, 1996), that is the overall number of carcasses that entered the population between the start ($t = 0$) and end ($t = T$) of the study, denoted N without subscript (Fig. 1).

To get N, we need to complexify the capture-recapture model in order to incorporate the processes in Fig. 1. In the context of carcass surveys, many variations of the Lincoln-Petersen estimator have been proposed to try and adapt that estimator for an open population. Their principle is to multiply p by a term that also accommodates the persistence process. In general, these estimators mostly focus on the bias caused by the early removal of carcasses by scavengers and decay. Only the most recent estimators also consider the possibility that carcasses persist undetected for long periods of time ("bleed through" *sensu* Wolpert, 2015).

- The Winkelman estimator (Winkelman, 1992) assumes that all fatalities occur at time 0, that no carcass was pre-existing before time 0, and that a single search is performed at time T. The estimator is then $\hat{N} = C/(\hat{p} \bullet \hat{\varphi})$ where φ is the probability for a carcass to persist from time 0 to time I, and C is the number of detected carcasses at time I.
- The Jones estimator (Jones et al., 2009) replaces the $\hat{\varphi}$ of the Winkelman estimator by $e^{-0.5 \bullet I/\bar{t}}$ where $\bar{t}$ is the average time to removal and I is the interval duration. By doing so they assume that time to removal is exponentially distributed. The 0.5 multiplication factor is an attempt at removing some of the bias caused by the violation of the assumption that all fatalities occur at the beginning of the interval. Jones et al. also recommend multiplying the denominator by

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