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Correcting for heterogeneous availability bias in surveys of long-diving marine turtles

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ABSTRACT

Effective conservation requires reliable data on the abundance and distribution of animals in space and time. During ship-based or aerial surveys for diving marine vertebrates such as sea turtles and marine mammals, a proportion of animals in a surveyed area will be missed because they are diving and out of view. While it is likely that dive and surface times vary with environmental conditions, such variation is rarely incorporated into survey-based research and its consequences for analyses of survey data are not well known. We quantified the effects of neglecting to account for variation in the dive-surfacing patterns of green turtles (*Chelonia mydas*) and loggerhead turtles (*Caretta caretta*) when analyzing boat-based survey data from a foraging ground in Western Australia. We found that analyses of turtle sightings data can be confounded by variation in the probability of turtles being at the surface where they are available for detection. For example, during the cold season in deeper areas in Shark Bay, green and loggerhead turtle density was underestimated by 45% and 21%, respectively, if extended dive times relative to population medians were not accounted for. These results have important implications for applications of survey data for a variety of taxa including other sea turtles, marine mammals and large sharks that are surveyed by boat or plane. Diving and depth use studies have much to contribute to the assessment and management of these groups, which include many species of conservation concern.

1. Introduction

Accounting for detection probability in field-based research is a pervasive challenge that has important implications for conservation applications of field data. When conducting visual surveys to estimate species abundances or analyze habitat–wildlife relationships, some animals will likely be missed (i.e., detection probability will be imperfect) and the proportion missed may be correlated with environmental variables, habitat features or animal characteristics such as age, size or sex (Buckland et al., 2004). If not addressed, non-random variation in detection probability may mask variation in abundance and alter inferences made from analyses of survey data (e.g. Moilanen, 2002; Gu and Swihart, 2004; Mazerolle et al., 2005). Since spatiotemporal analyses of abundance (e.g., time-series or regional comparisons) are fundamental to conservation planning, minimizing bias related to detection probability is an important methodological goal.

Accounting for detection probability in aerial or boat-based surveys of large-bodied, diving marine vertebrates (e.g., marine mammals and sea turtles) is particularly challenging. First, to be detected, an animal must be at a depth where it is visible to observers, which is often referred to as the probability of being 'available'. Availability is primarily a function of the animal's depth use patterns and water turbidity, although survey type is also influential; for example, during boat-based surveys observers often cannot see into the water and only animals at the surface are available, whereas during aerial surveys a proportion of submerged animals may be available. Second, a proportion of available animals will be missed by observers, which may vary with factors such as weather conditions and observer experience. Marsh and Sinclair (1989a) distinguished these components of detection probability for diving taxa and coined the terms 'availability bias' and 'perception bias', respectively, to refer to bias in abundance indices arising as their result. While these definitions are somewhat overlapping, they provide a useful framework for modeling different sources of imperfect detection probability and correcting abundance estimates to account for missed animals.

For taxonomic groups that dive for extended periods and spend a small proportion of time at or near the surface, availability bias is

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highly problematic (Kasamatsu and Joyce, 1995; Barlow, 1999; Okamura et al., 2006). This is because a large proportion of animals present in a surveyed area will be missed since they are submerged and out of view. Failing to account for availability bias for these taxa can therefore cause severe underestimates of abundance (Barlow, 1999). Furthermore, variation in dive and surface times may lead to heterogeneous availability patterns, which can bias or confound analyses of survey data (Kasamatsu and Joyce, 1995; James et al., 2006; Thomson et al., 2012a). Knowledge of dive-surfacing patterns is therefore important for analyses and applications of sightings data.

Two methods of accounting for availability bias during analyses of survey data for diving taxa have been employed. Marsh and Sinclair (1989a) determined an availability correction factor (ACF) for dugongs (*Dugong dugon*) in aerial surveys by comparing the proportion of animals seen at the surface versus beneath the surface in turbid water with this proportion in clear water. However, this method is not ideal if a clear water habitat is not available to use as a standard and, even in clear water, if some animals are too deep to be seen or are cryptic, using this proportion as a standard will lead to underestimates of abundance (Preen et al., 1997). More recently, diving data have been used to measure the proportion of time animals spend at visible depths and calculate an ACF based on these measurements. This method allows for more accurate estimates of abundance and has been applied in studies of many taxonomic groups including cetaceans (e.g., Laake et al., 1997; Barlow, 1999), sirenians (e.g., Pollock et al., 2006), sea turtles (e.g., Gómez de Segura et al., 2006; Eguchi et al., 2007) and large sharks that spend some proportion of time at or near the surface (e.g., whale sharks, *Rhincodon typus*, Rowat et al., 2009).

Currently, corrections for the diving component of availability bias are often hindered by limited dive data. As a result, ACFs are often poorly resolved, abundance estimates are uncertain and spatiotemporal analyses of survey data rest on the tenuous assumption that availability is uniform across all survey conditions (e.g., Kasamatsu and Joyce, 1995; Barlow, 1999; Gómez de Segura et al., 2006). Thus, applications of survey data are typically limited relative to their full potential. In particular, the effects of variation in dive-surfacing patterns on spatiotemporal analyses of survey data, which are fundamental to ecological and conservation applications, require quantitative evaluation (Kasamatsu and Joyce, 1995; Preen et al., 1997; Thomson et al., 2012a).

Here, we present a case study focusing on marine turtles on a coastal foraging ground in Shark Bay, Western Australia. Previously, we collected a large set of dive records for green turtles (*Chelonia mydas*) and loggerhead turtles (*Caretta caretta*) in Shark Bay and found variation in their dive and surface times related to habitat depth and seasonal water temperature (Thomson et al., 2012a). We concluded that this variation could confound or bias spatiotemporal analyses of transect survey data for turtles. Here, we quantify the effects of failing to account for such variation in availability when analyzing survey data. To do so, we use Bayesian statistical methods to incorporate depth- and temperature-related variation in marine turtle diving into several analyses of boat-based transect survey data from Shark Bay. We compare the results of each analysis with those obtained without accounting for variable availability – that is, using a single ACF for each species based on median dive and surface times for all availability corrections. We thereby illustrate the effects of unmodeled variation in availability on analyses of survey data and demonstrate analytical methods by which these effects can be minimized.

2. Materials and methods

2.1. Study site and species

Shark Bay, Western Australia (~25°45′S, 113°44′E) is a shallow (mostly <15 m), subtropical bay located approximately 800 km north of Perth, Western Australia. Our study area in the bay's Eastern Gulf near the Monkey Mia Resort (Fig. 1) is characterized by expansive shallow (<4.5 m) seagrass-dominated habitat separated and surrounded by deeper (>6.0 m) sand-dominated habitat. There are also extensive, shallow sand–seagrass flats near shore. Green and loggerhead turtles use Shark Bay as a feeding ground year round. Green turtles may forage for a variety of seagrasses, algae, scyphozoan jellyfish and ctenophores (Heithaus et al., 2002; Seminoff et al., 2006; Burkholder et al., 2011) while loggerhead turtles are known to feed generally on benthic invertebrates, particularly molluscs and crustaceans (e.g., Dodd, 1988; Limpus et al., 2001; Thomson et al., 2012b).

2.2. Boat-based strip transect surveys

Strip transect surveys were conducted at thirteen sites, each bisecting either a shallow, seagrass-dominated habitat (six sites) or a deep, sand-dominated habitat (seven sites). Transects were between ~3 and 4.5 km long and were initially established to measure the relative density of large marine vertebrates including bottlenose dolphins *Tursiops aduncus* and dugongs under predation risk from tiger sharks *Galeocerdo cuvier* in each habitat (e.g. Heithaus and Dill, 2002). Transects were run in small (<5 m) boats during warm and cold seasons (February–April and June–August, respectively) in 2003, 2004, 2006 (cold season only), 2007, 2008 and 2009 (warm season only). Transects at a given site within a single month were conducted at different times of day and in different directions (i.e., reversing start and end points), organized haphazardly, to minimize these possible biases. Observers were assigned quadrants to search so that all waters within 30 m of the boat, parallel to or ahead of the boat's position, were being viewed. A sighting was logged when one or more observers saw a turtle. Only turtles at the surface were counted because, from the low height of our small boats, it was often difficult or impossible to see into the water, especially as distance from the transect line increased. Furthermore, in Shark Bay, which is shallow and has a fine sand-silt substrate, turbidity conditions can change rapidly over short distances, making accounting for this aspect of availability bias very difficult. Sightings for which the species of turtle could not be confidently identified (6% of sightings) were excluded from analyses.

2.3. Availability bias related to dive-surfacing behavior

Dive-surfacing patterns have been quantified for green and loggerhead turtles in Shark Bay (Thomson et al., 2012a). Briefly, short-term (1–7-day) time-depth recorder (MK9, Wildlife Computers, Redmond, Washington, USA) deployments were used to collect dive data for 29 green and 46 loggerhead turtles between 2005 and 2008. The software MultiTrace Dive (Jensen Software Systems, Laboe, Germany) was used to analyze dive profiles. Hierarchical Bayesian regression models revealed a positive effect of habitat depth (estimated from maximum dive depths, see Thomson et al., 2012a) and a negative effect of daily water temperature (i.e., seasonal variation between ~18 and 30 °C) on dive and surface times, although temperature effects were not significant in all cases. The regression equations were used to predict dive and