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Improving in-water estimates of marine turtle abundance by adjusting aerial survey counts for perception and availability biases

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ABSTRACT

Aerial surveys are often used to estimate wildlife abundance. The probability of detecting an animal during a survey involves two processes: (1) availability bias when animals present in the search area are not available for detection and (2) perception bias, when some animals potentially visible to observers are missed. Estimating these two sources of bias can lead to improved abundance estimates. However, to date, no marine turtle aerial survey has quantified both biases. To improve in-water marine turtle abundance estimates from aerial counts we estimated: (1) perception bias using independent tandem observers and mark recapture models, and (2) availability bias by quantifying the effect of turtle diving behaviour and environmental conditions on the detection probability of turtles. We compared unadjusted and adjusted abundance estimates to evaluate the effects of these detection biases in aerial surveys. Adjusted data produced a substantially higher estimate of turtles than the unadjusted data. Adjusting for availability bias increased the estimates 18.7 times; adjusting for perception bias resulted in a further 5% increase. These results emphasize the need to consider availability and perception corrections to obtain robust abundance estimates. This approach has application for aerial surveys for other marine wildlife including marine mammals and large sharks.

1. Introduction

All species of marine turtles are listed as threatened (IUCN, 2014) and are subject to active conservation programs in many parts of the world. Reliable information on the abundance and distribution of marine turtles is important for their successful management and conservation (Eguchi et al., 2007; Thomson et al., 2013). Such information can enable population trends to be assessed, provide a context for evaluating anthropogenic and natural threats, including the risks of population collapse, and assist in identifying priority areas for management (Hamann et al., 2010; National Research Council, 2010; Roos et al., 2005).

Marine turtle abundance has been estimated using a variety of techniques (e.g., capture–mark–recapture, nesting beach monitoring, tagging and in-water surveys) from a range of platforms (e.g., land, aerial or boat-based) (e.g.,(Chaloupka and Limpus, 2001; Broderick et al., 2002; Seminoff et al., 2014). However, most work to date has estimated abundance from counts of nesting female turtles (Stokes et al., 2014). Nesting animals are accessible, and studying turtles on land is logistically easier and less expensive than when they are at sea (Seminoff et al., 2003; Stokes et al., 2014). However, female marine turtles spend most of, and male turtles all of, their lives at sea. In-water surveys are thus essential to ensure that abundance estimates cover both male and female turtles across a broad range of age classes and in feeding as well as breeding habitats (Chaloupka and Musick, 1997; Seminoff et al., 2003).

Aerial surveys enable the abundance of subadult and adult turtles to be estimated over large tracts of sea (Cardona et al., 2005; Epperly et al., 1994; Gómez de Segura et al., 2003; McDaniel et al., 2000; Seminoff et al., 2014). However, aerial surveys of in-water marine wildlife fail to meet a fundamental assumption of line transect sampling: that all animals on the transect line are detected (Buckland et al., 1993). This limitation can be mitigated by correcting abundance estimates to compensate for this reduced probability of detection. Nevertheless, it remains challenging to obtain defensible estimates of detection

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probability, particularly for animals such as marine turtles that only spend a small proportion of their time at the surface (Marsh and Sinclair, 1989a; Okamura et al., 2006). Earlier studies have estimated detection probability as a single constant, using diverse methods, including multiple independent observers, concurrent aerial and ship surveys, and estimates of breathing rates (obtained external to the survey) for the target species (Buckland and Turnock, 1992; Laake et al., 1997).

Marsh and Sinclair (1989a) recognised that the probability of detection of marine wildlife involves two processes: (1) availability bias, which occurs when submerged animals, although present in the survey area, are not available for detection due to environmental conditions (e.g., water turbidity, sea state, cloud cover, surface glare) and animal characteristics (e.g., group size, body colour, body size, diving patterns); and (2) perception bias, which results from observers missing animals that are available for detection. Availability and perception biases interact and are not mutually exclusive.

Estimating these two sources of bias at the level of animal sighting leads to improved abundance estimates (see Pollock et al., 2006; Hagihara et al., 2014). Most efforts along these lines have been directed at improving abundance estimates for marine mammals. Refinements have been achieved by deploying telemetry devices to record diving and surfacing patterns of individual animals and using the resultant data to estimate the proportion of time that animals are available for detection across various environmental conditions and for different animal characteristics (e.g., life stage, pod composition, sex; see (Hagihara et al., 2014). In contrast, aerial surveys of marine turtles have only recently addressed availability bias by incorporating information on animal diving and surfacing patterns (e.g., Gómez de Segura et al., 2006; Seminoff et al., 2014). To our knowledge, no marine turtle aerial surveys have quantified both perception bias and availability bias or compensated for the heterogeneous environmental conditions typical of coastal environments.

To address these issues for an aerial survey of turtles, we (1) corrected for perception bias following the method of Pollock et al. (2006); (2) developed correction factors to compensate for availability bias at the level of individual sighting by (a) conducting experimental trials with a 'marine turtle Secchi Disk' to identify the depth of detection zones below the water surface where turtles are visible to aerial observers under different environmental conditions and (b) estimating the proportion of time that turtles spend in these detection zones by analysing time-depth recorder data from devices deployed on free-living turtles; (3) applied the resultant correction factors to aerial survey counts to improve abundance estimates; and (4) compared unadjusted and adjusted abundance estimates to evaluate the effects of failing to account for availability and perception biases in aerial surveys of subadult and adult marine turtles. The approach considered here and our suggestions for future improvements of in-water marine turtle abundance are widely applicable to abundance data from aerial and vessel surveys of other marine wildlife.

2. Materials and methods

2.1. Study site

Torres Strait (S 10° 29.59″, E 142° 10.44″), between Australia and Papua New Guinea, is mainly shallow (<20 m) with more than 200 islands, cays, and sandbanks (Harris et al., 2008) scattered over ~45,000 km^2 (~150 km north–south and ~300 km east–west, Fig. 1). Torres Strait provides foraging grounds for immature and adult turtles and acts as a corridor for turtles that migrate from eastern Indonesia, the Arafura Sea region, and the Gulf of Carpentaria to breeding sites in eastern Torres Strait and the northern Great Barrier Reef (nGBR) (Limpus and Parmenter, 1986). Three species of marine turtles nest and forage in Torres Strait: the green turtle, *Chelonia mydas*; the hawksbill turtle, *Eretmochelys imbricata*; and the flatback turtle, *Natator depressus* (Miller and Limpus, 1991). The loggerhead turtle, *Caretta caretta*, the olive ridley turtle, *Lepidochelys olivacea*, and the leatherback turtle, *Dermochelys coriacea*, are also found in Torres Strait waters. Nonetheless, green turtles dominate the Torres Strait marine turtle community; the other five species occur at much lower densities (Miller and Limpus, 1991). Consequently, green turtle behavioural data (obtained external to the survey) were used for estimating availability bias.

2.2. Standard aerial survey

A systematic aerial survey was conducted in central and western Torres Strait between 11 and 28 November 2013. Eastern Torres Strait, an area with important green turtle nesting grounds, was not surveyed (Fig. 1) because the survey was part of a long-term time series for dugongs, which occur there only at very low densities. The survey occurred at the beginning of green turtle nesting in the region (Limpus et al., 2003).

The survey was conducted using a 6-seat, high-wing, twin-engine Partenavia 68B flown 500 feet (152 m) above sea level along predetermined transects as close as possible to a ground speed of 100 knots (Fig. 1; Sobtzick et al., 2014). A strict ceiling was imposed on environmental conditions (no precipitation, sea state <4); 97% of the survey was conducted in Beaufort sea state <4.

The strip transect technique (a form of distance sampling that assumes constant likelihood of detection across a defined strip) was developed experimentally by Marsh and Sinclair (1989a,b) and Pollock et al. (2006) for the dugong, *Dugong dugon*, a species that generally surfaces for only a few seconds. A tandem teams of two independent, trained observers sat on each side of the aircraft and scanned a transect 200 m wide demarcated using fibreglass rods attached to artificial wing struts on the aircraft. Each transect was divided into four horizontal substrips (very high, high, medium, and low) by marks on the wing struts.

The two members of each tandem team operated independently and could neither see nor hear each other when on transect. Each observer recorded sightings onto separate tracks of an audio recorder. The recording of the sightings in the four substrips enabled the survey team to decide when reviewing the recordings if simultaneous sightings by tandem team members were of the same group of animals. This protocol was used instead of an inclinometer as the sighting rate was often very high and an inclinometer requires the observer to take their eyes off the water to read it, potentially resulting in missed animals.

All sea turtle sightings were recorded (but not to species), including those that did not fall within the transect strip. In such cases, the animals were recorded as 'inside' (below) or 'outside' (above) the transect strip to reduce the likelihood of an observer recording a sighting as in the transect when it was just outside. Sightings outside the transect were not used in the analyses.

Three combinations (teams) of tandem observers were used during the survey for logistical reasons. The survey leader collected data on environmental conditions at the beginning of each flight (cloud cover, cloud height, wind speed and direction, and air visibility) and for each transect (cloud cover). Sea state, water visibility, and glare (each side of the aircraft) were recorded every few minutes during each transect and whenever conditions changed using standard categories (Sobtzick et al., 2014). The survey area was divided into spatial blocks of varying sampling intensity with transects of varying lengths (Fig. 1 and Supplementary Table 1).

The aerial survey data were used to estimate the relative abundance of marine turtles following the methodology of Pollock et al. (2006). This method corrects for (1) sampling fraction, (2) perception bias, and (3) availability bias (*sensu*; Marsh and Sinclair, 1989a). Corrections for the biases were applied separately for each turtle sighted as an individual, and for each group of turtles (turtles seen in quick succession).