Australian Government
Australian Fisheries Management Authority

JCU
JAMES COOK UNIVERSITY

AFMA FINAL RESEARCH REPORT

Report Number R99/0497

Report Title
IMPROVING THE ACCURACY OF AERIAL SURVEYS FOR DUGONGS.

Report Date
December 2004

AFMA Report Number R99/0497

IMPROVING THE ACCURACY OF AERIAL SURVEYS FOR DUGONGS.

KENNETH H. POLLOCK, Zoology, Biomathematics, and Statistics, North Carolina State University, Raleigh, NC 27695-7617, USA

HELENE D. MARSH, Tropical Environment Studies and Geography, James Cook University, and CRC Reef Research Centre, Townsville, 4811, Australia

IVAN R. LAWLER, Tropical Environment Studies and Geography, James Cook University, and CRC Reef Research Centre, Townsville, 4811, Australia

MATHEW W. ALLDREDGE, Biomathematics Program, Department of Statistics, North Carolina State University, Raleigh, NC 27695-8203, USA

AFMA Project Number R 99/0497

December 2004

AFMA Report Number R99/0497

Australian Fisheries Management Authority Torres Strait Research Program Final Report

This report contains the results of a project entitled ‘Improving the accuracy of aerial surveys for dugongs’. This research was carried out by James Cook University in collaboration with researchers from North Carolina State University. The project was funded by AFMA and JCU. The empirical data on which the research was based was funded by various funding agencies including the Pew Foundation, the Great Barrier Reef Marine Park Authority, the western Australian Department of Conservation and Land Management and the Australian Research Council as detailed in the acknowledgments.

The report should be cited as:

Pollock, K.H., H.Marsh, I.R.Lawler and M. W.Alldredge (2004). Improving the accuracy of aerial surveys for dugongs. Final report. AFMA/JCU Final Report, Canberra, Australia.

A paper arising from the report is in press after international peer review as:

Pollock, K., H. Marsh, I. R. Lawler and M. W. Alldredge, M. W. In press. Estimating animal abundance in heterogeneous environments: an application to aerial surveys for dugongs. Journal of Wildlife Management.

A parallel report has been submitted to GBRMPA.

Published: December 2005

National Library of Australia Cataloguing-in-Publication data:
Bibliography.

ISBN 0 8644337374

1. Subject keywords: Torres Strait, Dugong, Population Surveys, Aerial Survey Methodology
Helene Marsh II. Publishing Research
James Cook University. III. Australian Fisheries Management Authority (Australia).
R 99/0497

TABLE OF CONTENTS

NON-TECHNICAL SUMMARY

Aerial surveys are the established method of estimating dugong abundance in large (30,000 km^2) regions such as Torres Strait. However, not all the dugongs present in the survey region are seen by the observers in the survey aircraft for three reasons:

  - Torres Strait is too large to attempt a complete count. Thus the area has to be sampled and the resultant population has to be corrected for the probability of sampling a particular area.
  - Not all animals can be seen by the observers as the water is turbid in most areas.
  - Some animals which are available to be seen are missed by the observers.

- We carried out experiments using dugong models to determine how close to the surface dugongs had to be seen to be visible from a survey aircraft at a range of depths, turbidities and sea states. We also deployed timed depth recorders on 15 wild dugongs to obtain their dive profiles. This enabled us to calculate the probability of a dugong being available in different areas based on depth, turbidity, and sea state.
- We calculated the proportion of dugongs that were available to observers but missed during the survey by using two observers on either side of the aircraft. These observers could not hear or see each other and reported their sightings into separate tracks of a two-track tape recorder. We compared their observations using a computer program to determine the likelihood of the observers in each team missing a visible dugong.
- We developed mathematical methods to use all this information to estimate the dugong population.
- We used this new technique to recalculate the dugong populations of Torres Strait and the Great Barrier Reef region north of Cooktown based on recent aerial surveys.
- For Torres Strait, the new method produced a smaller estimate (11,956 versus 14,106 dugongs) and a very much smaller standard error (1,189 versus 2,314 dugongs), whereas the new method produced slightly larger estimates (mean 9,855 versus 9,193 dugongs, standard error 1,184 versus 917 dugongs) for the Northern Great Barrier Reef survey.
- These new population estimates are being used as the basis of estimating a sustainable catch for the Torres Strait dugong fishery and for Indigenous hunting in the northern Great Barrier Reef region off Cape York peninsula.

ACKNOWLEDGMENTS

This research was funded by several agencies including the Australian Fisheries Management Authority, the Australian Research Council, Conservation and Land Management Department in Western Australia, the Great Barrier Reef Marine Park Authority, the Pew Foundation, Sea World, Hope Vale Aboriginal Community and James Cook University. We particularly thank all those who supported us in the field work and data analysis including: W. Blanshard, L. Chilvers, S. Delean, N. Gales, A. Hodgson, D. Holly, D. Kwan, T. Long, T. Preen, our pilots, aerial survey crews, the crew on the Sea World boat, and dugong catching crews including the 'mob' from Hope Vale Aboriginal Community. M. Bigazzy of the University of Queensland assisted with the making of the dugong models. A. Hodgson and L. Chilvers provided access to unpublished data. Fig. 1 is copied with permission of the Asian Journal of Marine Biology. We thank 2 anonymous referees, an associate editor of the *Journal of Wildlife Management* and B. Brunhuber for important editorial assistance and the Torres Strait Scientific Advisory Committee for their support and guidance.

BACKGROUND

Since at least the 1940s, aerial surveys have been widely used to estimate the size and density of populations of wildlife including marine mammals (e.g., dolphins, Holt and Powers , 1982; dugongs, Marsh and Sinclair 1989a, b; right whales, Hain et al. 1999, manatees, Wright et al. 2002), terrestrial mammals (e.g., African ungulates, Jolly 1969; white tailed deer, Rice and Harder 1977; kangaroos, Caughley and Grigg 1981; mule deer, White et al. 1989; impala, Peel and Bothma 1995) and birds (e.g., emus, Caughley and Grice 1982; bald eagles, Grier et al. 1981; mottled ducks, Johnson et al. 1989).

Much of the information used to manage dugong populations in Australia has been provided by aerial surveys using standardized techniques developed by Marsh and Sinclair (1989a, b). Dugong surveys are typically conducted every 5 years and cover $\leq$30,000 km^2 of coastal waters of extremely variable turbidity (see Marsh et al. 2002 for an overview). The surveys have been used to identify the most important dugong habitats in Northern Australia (Marsh et al. 2002), as well as in the Arabian region (Preen 1989). Survey results have been used as the basis of conservation planning for dugongs in many parts of northern Australia, especially the Great Barrier Reef Marine Park, where most of the important dugong areas have high levels of protection (Marsh et al. 2002; in press). The changes in dugong numbers observed by a temporal series of surveys in the Great Barrier Reef region between 1986 and 1994 were the catalyst for establishing 15 Dugong Protection Areas (Marsh 2000) in which commercial gill netting was controlled to reduce incidental dugong mortality.

In Torres Strait, between Australia and Papua New Guinea, Indigenous hunting is the most significant human impact on the dugong population (Marsh et al. 1997a, 2004). The results of the surveys of this region have also been used as the basis for stock assessment (Marsh et al.1997b; Marsh et al. 2002, 2004) using the Potential Biological Removal Technique (Wade 1998) and for Population Viability Analysis (Heinsohn et al. 2004).

There are many challenges in obtaining defensible estimates in aerial surveys, because not all animals are detected. Caughley (1977) and Pollock and Kendall (1987) pointed out that all wildlife surveys suffer from this problem and that it is much more serious than many biologists recognize. In their paper on dugong aerial survey design, Marsh and Sinclair (1989a) emphasized that it is important to separate detection probability into processes accounting for animals not being available and animals not being detected even if available, especially in heterogeneous environments. They also presented dugong population estimates that allowed for both processes. Here we substantially refine their approach, especially the estimation of non-availability. We illustrate our revised methodology with absolute abundance estimates of dugongs from 2 recent aerial surveys. Our approach illustrates the importance of, and potential solution to, a common problem for aerial surveys of most wildlife species in heterogeneous environments. It also underpins updated assessments of the sustainability of the Torres Strait dugong fishery (Heinshohn et al. 2004; Marsh et al, 2004).

NEED

Aerial surveys are the established method of estimating dugong abundance in a region such as Torres Strait. However, not all the dugongs present in the survey region are seen by the observers in the survey aircraft for three reasons:

- Torres Strait is too large to attempt a complete count. Thus the area has to be sampled and the resultant population has to be corrected for the probability of sampling a particular area.
- Not all animals can be seen by the observers as the water is turbid in most areas.
- Some animals which are available to be seen are missed by the observers.

In order to undertake stock assessments for dugongs, it is essential to develop methods which provide robust estimates of absolute population size. This research provided a method of overcoming the spatial and temporal heterogeneity in dugong sightability to overcome the biases inherent in the survey technique.

OBJECTIVE

To develop methodology to obtain an absolute estimate of the number of dugongs in Torres Strait

METHODS

Field Methods

The standard dugong aerial survey methodology is discussed in detail in Marsh and Sinclair (1989a). Transects chosen under a stratified random sampling design were flown at standard height (137 m) and speed (185 km/h) in Partenavia 68B twin-engine aircraft. We observed a strict ceiling on acceptable weather conditions for survey flights. The 6-member crew included a pilot, survey leader, plus tandem teams of 2 independent observers on each side of the aircraft (Fig. 1). There was an area under the aircraft that could not be surveyed. The independent observers on each side of the aircraft searched a 200 m-wide strip, defined by transect markers that were fishing rod blanks attached to artificial wing struts. Distance categories (50, 100, and 150 m) within the strip were marked by color bands on the artificial wing struts. The members of the tandem team of observers on each side of the aircraft could not see or communicate with each other. They recorded their observations of dugong onto separate tracks of a tape recorder.

We obtained additional data on animal availability from 2 sources, external to the regular aerial surveys: an experiment using artificial dugong models, and observations of telemetered dugongs. We constructed 2 dugong models with marine plywood and fibreglass, which resembled the view of individual dugongs of different sizes (total lengths 2.0 and 2.5 m) as seen from above by aerial survey observers. The position of the models in the water column was regulated by a rope and pulley system operated from the stern of a research vessel. During experimental trails, 2 observers hovered above the research vessel in a Bell Jet Ranger helicopter at the height and position relative to the in-water models of a dugong aerial survey aircraft. When the helicopter and models were in position, each model was pulled slowly from the sea floor to the surface. Each observer independently recorded the time (accurate to 1 s) that a model became recognisable as a dugong. The depth at which this occurred was estimated by matching these times to automated data collected on a timed depth recorder (model MK7, Wildlife Computers, Woodinville, WA, USA) attached to the dorsal surface of each model. These timed depth recorders were accurate to 0.25 m, recorded depth every second, and were synchronized with the watches of the observers in the helicopter. Three replicate trials were recorded for each model under the range of conditions of water turbidity, depth, and sea state that encompass the conditions encountered during aerial surveys of dugongs.

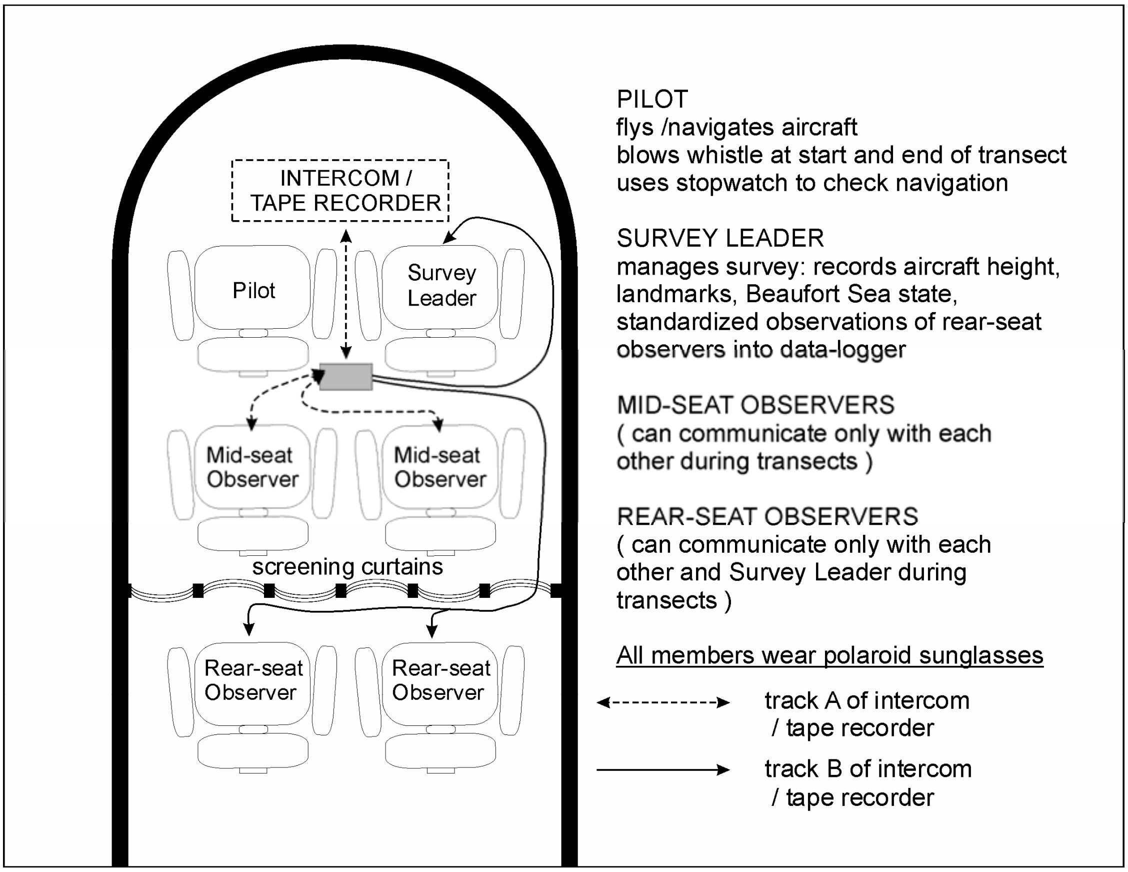

Fig. 1. Interior aircraft design showing the configuration of the seating arrangement and how the 2 observers on each side maintain independence by using separate tracks of tape recorders and screening curtains. (Adapted from Marsh and Sinclair 1989a and reprinted from the *Asian Journal of Marine Biology*).

We caught 15 wild dugongs and attached a floating transmitter package to each, tethered to the tailstock harness by a 3-m nylon rod using techniques described in Marsh and Rathbun (1990). The transmitter packages contained a very high frequency (VHF) transmitter and an ST-14 platform transmitter terminal (PTT) satellite tag (Telonics, Mesa, Arizona). Timed depth recorders were attached just above the harness, effectively adjacent to the dugong's tailstock. All harness attachments were designed to release automatically from the animals for retrieval. Both MK4 and MK7 timed depth recorders were used on live dugongs. The former recorder sampled depth at 5-s intervals with depth resolution of 40 cm. Therefore, all data were analyzed assuming a depth resolution of 40 cm (Chilvers et al. 2004).

The minimum depth counted as a dive was set at 1.5 m, to allow for: (1) the timed depth recorder's sensor resolution depth of 40 cm; (2) the location of the timed depth recorder's tags on the dugong's tailstock, which is commonly higher than the rest of the body, particularly while the dugong is feeding (Anderson 1998); (3) fluctuation of the position of the tail as the dugong moves and; (4) drift in the zero reading and possible influences of wave action.

Statistical Methods

Population Estimation Procedure.—The basic detection probability model now in use (e.g., Williams et al. 2002:244) uses the following probability of detection for animal *j*:

$$\hat{p}_j = p_b \hat{p}_{dj} .$$

The first term was the probability of sampling a strip in block (or strata), *b*, which was simply the proportion of the area in block *b* sampled. The second term ($\hat{p}_{dj}$) estimated the probability that animal *j* was detected, given that it was in a sampled strip.

We extended this model to account for the fact that some animals could have been unavailable. The equation was

$$\hat{p}_j = p_b \hat{p}_{aj} \hat{p}_{dj} .$$

Here $\hat{p}_{aj}$ estimated the probability that individual *j* was available for detection, while $\hat{p}_{dj}$ estimated the probability that an individual *j* was detected, conditional on its being available.

We then used a version of the generalized Horvitz-Thompson population estimator originally applied to closed capture-recapture models by Huggins (1989, 1991) and Alho (1990)

$$\hat{N} = \sum_{j=1}^{n} [1/\hat{p}_j]$$

where *n* was the number of distinct dugongs detected in the whole survey.

Variance and Standard Error Estimation.—We found it difficult to extend the analytical large-sample variance results used by Huggins (1989, 1991), due to the complexity of the problem considered here. Furthermore, we wished to obtain variance and standard error estimates that did not depend on asymptotic or large-sample results. Therefore, we used a Monte Carlo simulation method to obtain standard errors. This is becoming a common method of obtaining measures of uncertainty in fisheries models (e.g., Restrepo et al. 1992). All sources of variation are included and there are no approximations if sufficient simulation runs are used.

In our simulations using MATLAB®, we generated 1000 independent replicate population estimates for each of the *b* blocks (strata) and also the overall population estimates for the survey. We then calculated mean, variance, and standard deviation (which was an estimate of the standard error for each stratum population estimate and for the overall population estimate).

For each replicate, *i*, we specified the number of dugongs in each block (N_{b_i}) as the estimated population size for that block. We then generated the number of dugongs in the sampled strips for each block, *b*, as a Normal random deviate with mean $N_{b,i}\,p_b$ and variance $N_{bi}\,p_b\,v$. Here *v* was a variance inflation factor to allow for variation above that due to a random (Poisson) distribution, caused by clumping of groups. It was calculated from the raw counts on each transect in each block. We considered *k* transects in a block of unequal lengths, each with a count, y_k, and area, a_k and defined

$$Y = \sum_{i=1}^{k} y_i \text{ and } A = \sum_{i=1}^{k} a_i \, .$$

Then, following Buckland et al. (2001:79), we obtained the variance inflation factor

$$v = \frac{\widehat{\mathrm{var}}(Y)}{Y}$$

where

$$\widehat{\mathrm{var}}(Y) = \frac{A\sum_{i=1}^{k} a_i \left(\frac{y_i}{a_i} - \frac{Y}{A} \right)^2}{k-1}$$

We next assigned each simulated dugong and availability class, based on drawing an observation from a multinomial distribution with probabilities estimated from an independent systematic random sample of points along the transects. To account for error in estimating availability probabilities, we drew the availability probabilities (that were <1.0) for each availability class specified in Table 1, each from independent normal distributions with the appropriate estimate in Table 1 for the mean and standard deviation equal to the estimation (standard) error . (In the extremely rare case that a value was not between 0 and 1 we truncated it). We used these availability probabilities to stochastically assign each dugong to an available or non-available category. Each available dugong was also assigned stochastically to the port or starboard side.

To account for error in estimating the detection probability given available, we followed a similar approach and drew 4 detection probabilities (defined separately for front and rear observers and side of aircraft for each survey team) from independent normal distributions with the same mean and standard error as the survey estimates (Table 2). (We note that there were 2 survey teams but they surveyed different transects). We stochastically assigned each available dugong on each side a capture history based on the appropriate detection probabilities.

We grouped the capture histories across blocks and calculated the probability of detection given the dugong was available for each observer on each side of the plane for the survey, using the Generalized Lincoln Petersen estimates presented later. Finally, we calculated the population size estimates for each block, $\hat{N}_{b\,i}$, and then for the whole population for this replicate.

Estimation of the Probability of Being Available.—Diving data were analyzed using Multitrace$^{®}$ (Jensen Software Systems, Laboe, Germany) to produce summary statistics for each dive. Zero-offset drift in the depth values for each tag was corrected manually within Multitrace$^{®}$. The analysis of the dive records enabled us to estimate $\hat{p}_{a,i}$ as the average proportion of time the dugongs spent in the various depth ranges (identified using the physical models) under various turbidity and sea surface conditions. The probability estimates for water in which: (1) the bottom was visible but unclear, or (2) the water was turbid, were calculated over all dive records as these conditions occur in waters spanning the depth ranges that the dugongs use. The corresponding probability estimates for the availability of dugongs in clear water in which the bottom was not visible were based on records from dives in >5 m of water (below 5 m in clear water conditions fall into category 1, above). We used 4 dugongs with mean, median, and modal maximum dives of >6 m and a corresponding subset of the data from 1 dugong that spent considerable time in water >5 m deep. Availability probabilities were calculated for individual dugongs. We assumed independence of diving behavior, and hence of availability, of members of the same group in the analyses below.

Assumptions for the availability process estimation were:

1. The depth at which dugong models become visible was measured without error;
2. The dugong models exhibit detectability similar to real dugongs (i.e., the depth at which dugong models became visible was the same as for real dugongs in water of all depths);
3. Depth profiles of individually monitored dugong were representative of the whole population of dugongs being studied in the aerial survey;
4. The aircraft speed was fast enough that the dugongs were viewed "instantaneously" and, thus, were either available or unavailable (i.e., a binomial model applies);
5. There was independence of diving behavior, and hence of availability, of individual dugongs irrespective of their proximity to each other; and
6. The availability probability of individual dugongs was the same irrespective of the presence of other dugong in a group.

There was only small measurement error in the depth at which individual dugong models appeared (assumption 1).

We made considerable effort to make the models as realistic as possible but assumption 2 was very difficult to test. It was not possible to exactly match the depth of the zone of visibility of the models with the zone of detectability of the telemetered dugongs to calculate p_a, because of the limitations of measuring the depths of the telemetered dugongs explained above. In addition, we were concerned about the appropriate depth ranges to calculate the estimates. These estimates will improve when dive profiles become available from dugongs fitted with GPS tags that enable the depth of the water in which each dive occurs to be located with a resolution of a few meters.

We could not be sure that assumption 3 was satisfied. Only 15 dugongs (but a total of 39,500 dives) were monitored. The effects of dugong sex, location, time of day, and tide cycle on diving rates (dives per hour), mean maximum dive depths, duration of dives, and time spent in very shallow water ($\leq$1.5 m) were investigated using weighted analysis of variance. Individual variation dominated all other effects (Chilvers et al. 2004).

Based on an aircraft speed of 185 km/h or 51 m/s, we believe that assumption 4 was reasonable, particularly as observers had to scan back and forth across a 200 m strip.

Dugongs are generally observed singly or in very small groups. An extreme alternative to assumption 5 would be synchronous availability of dugongs in a group. We investigated this assumption by examining the surfacing behavior of groups of dugongs in clear shallow water using aerial video footage obtained from a video mounted from helium filled aerostat (blimp) (A. Hodgson, James Cook University *personal communication*). The intervals between successive surfacing events by pairs of different dugongs in the same group indicated that dugongs in a group were not synchronously available to observers in the survey aircraft. Our study using the models gave us information on the probability of being available for individual dugongs, not dugongs that occurred in groups. We suspect that assumption 6 was reasonable for 2 reasons. First, most group sizes were very small and, second, the protocol used for dugong aerial surveys required a rapid constant aircraft speed and no additional time off line to scan groups. To the extent that the assumption was violated, the probability of being available would be larger for dugongs in larger groups due to observers spending more time looking in the vicinity of the group, thereby violating the instantaneous scan assumption (assumption 4). Further, cows with calves were likely to be more available than cows without calves, but we had to assume that they had the same availability.

Modeling the Perception Process.—The data for estimation of p_d was obtained during the regular aerial survey and analyzed using the Lincoln-Petersen method with 2 independent observers, as described in detail in Marsh and Sinclair (1989a). For 1 side of the aircraft, the probability of detection by each observer (Seber 1982, p.59) was:

$$\hat{p}_1 = X_{11} / n_2 \ \ and \ \ \hat{p}_2 = X_{11} / n_1$$

where X_{11} was the number of dugongs detected by both observers, and the n_i was the total number detected by observer i. The probability of detection by ≥1 observer on 1 side of the aircraft was

$$\hat{p}_d = 1 - (1 - \hat{p}_1)(1 - \hat{p}_2) \,.$$

Assumptions for the perception estimation were:

1. Counts within the strip of 200 metres were accurate;
2. There were no matching errors between the 2 observers, so that the assignments to those seen by 1 observer or both were accurate;
3. Detection probabilities for a given observer (given the animal was available) was equal for all dugongs; and,
4. Individual sightings of dugongs by different observers were independent.

We minimized measurement error in assigning a dugong to be inside or outside the 200-m strip (assumption 1) by using the fishing rod blanks as transect markers, which were flown from the aircraft and clearly delineated both the inner and outer boundaries of the transect, appearing to the observers as lines on the water. In addition, observers were asked to record all dugongs sighted, even if they were outside the strip, so that there was no incentive for them to misclassify a sighting. The use of dual-track tape recorders helped minimize matching errors (assumption 2). Marsh and Sinclair's (1989a) approach does not allow heterogeneity of detection probabilities for different individual dugongs (assumption 3), however, we discuss below how to model such effects based on individual covariates such as turbidity. If undetected, such heterogeneity would mean estimates of detection probability have some positive bias; consequently, population estimates would have negative bias. Independence of observers (assumption 4) was achieved by having curtains in the aircraft so that the 2 tandem observers (mid and rear) on each side of the plane could not see each other. In addition they were acoustically isolated by the intercom system. Independence of sightings between animals is a common assumption in most uses of capture models, but is violated when animals occur in clusters. We thought this was unimportant here because the cluster sizes were very small.

We used MARK (White and Burnham 1999) for all analyses of the perception process. We fitted generalized Lincoln-Petersen models that allowed for detection probability conditional on availability to vary by seat (mid or rear), side (port or starboard), and individual survey team. We used Akaike's Information Criterion corrected for small sample bias (AIC_c; Burnham and Anderson 1998) to pick the simplest model that adequately explained the data. In addition, MARK was used to determine if the detection probability (conditional on availability) was dependent on individual group covariates such as number of dugongs in the group, number of calves, turbidity and Beaufort Sea State. Due to the small number of detections in some strata, MARK was run at the whole survey level rather than at the individual stratum (block) level.

We also investigated using distance class (0-50, 50-100,100-150, and 150-200) as a covariate in MARK so that we could use the double observer line transect methodology of Alpizar and Pollock (1996), Manly et al. (1996), and Borchers et al. (1998a, b). Although we found no clear decline in detection with distance, we detected a large amount of measurement error in the assignment of dugong sightings to distance classes within the transect strip. The aviation safety authority permitted us to mount only 2 transect markers on each side of the aircraft. Thus, distance categories within the strip were marked only by color bands on the 'pseudo wing struts' (sensu Marsh and Sinclair 1989a), a less than satisfactory way of delineating distance classes for animals such as dugongs which surface cryptically and for only 1-2 s (Chilvers et al. 2004). Alpizar (1997) and Chen and Cowling (2001) have examined the effects of measurement errors on line transect theory and shown they can cause serious bias. We decided, therefore, that it was inappropriate to use distance as a covariate in these analyses.

Clustering Model Extension.—Although we believe that our base model was the best to use for the dugong aerial survey analysis, we also extended our base model estimation procedure. We recalculated everything on a cluster basis using the modified equation:

$$\hat{N} = \sum_{i=1}^{g} [s_i / \hat{p}_i]$$

where g was the number of clusters detected, s_i was the group size and p_i was the total detection probability for the i^{th} cluster. We also extended the variance estimation procedure. This approach requires the unreasonable assumption that members of each cluster function in a totally dependent synchronous manner with respect to being available and being detected but is included for comparison.

Surveys Reanalyzed. — We used the methods outlined above to carry out a detailed reanalysis of two surveys that were originally analyzed using the methodology of Marsh and Sinclair (1989a): Northern Great Barrier Reef in 2000 and Torres Strait in 2001.

RESULTS

Sea state, turbidity and depth all influenced the probability of an animal being available (Table 1). Under conditions of optimal sea state the probabilities ranged from 1.0 in clear to <0.5 in turbid water. A change in Beaufort sea state from optimal (≤2) to marginal (>2) made the greatest difference to the availability of dugongs in deep clear water, reducing the mean probability by 36%.

Table 1. Availability probability estimates (SE's) for various strata of survey depths and turbidities calculated from data on artificial dugong models and the individual dive profiles of telemetered wild dugongs.

	Water Quality	Depth Range	Visibility of Sea Floor	Maximum Depth of Visibility of Models[a] (m)	Depth Zone of Visibility (m)[b] to calculate p_a	p_a (SE)
Optimal Sea State						
	Clear	Shallow	Clearly visible	Bottom	All	1
	Variable	Variable	Visible but unclear	2.44	2.5	0.65 (0.0452)
	Clear	>5m	Not visible	4.32	4.0	0.46[d] (0.057)
	Turbid	Variable	Not visible	1.23	1.5[c]	0.47 (0.0525)
Marginal Sea State						
	Clear	Shallow	Clearly visible	Bottom	Bottom	1
	Variable	Variable	Visible but unclear	1.21	1.5[c]	0.47 (0.0525)
	Clear	>5m	Not visible	0.69	1.5[c]	0.30[d] (0.0724)
	Turbid	Variable	Not visible	1.43	1.5[c]	0.47 (0.0525)

[a] Averaged for models 2.0 and 2.5 m long.

[b] Maximum depth used to calculate p_a from the telemetered animals.

[c] Based on minimum dive depth detectable on 15 telemetered wild dugongs (See text for explanation).

[d] Based on records from 4 dugongs with mean, median, and modal maximum dives of >6 m and a corresponding subset of the data from 1 dugong that spent considerable time in water >5 m deep (See text for explanation).

Comparing models for the Torres Strait 2001 survey (Table 3), we found that the most strongly supported model (98.7% of AIC*c* weight) included distinct detection probabilities for each of the 8 observers (4 in each aircraft; Table 2). There were large differences between observers' detection probabilities, ranging from 0.24 (SE = 0.0629) to 0.90 (SE = 0.0548). Although we do not present the result here, we also found that models including other covariates were not important.

Table 2. Detection probability estimates (standard errors) given animals are available, computed by program MARK for a survey of dugongs in the Torres Strait in 2001 using the most strongly supported model under Akaike's information criterion, which included survey team, position in the aircraft (front or rear), and side of aircraft (port or starboard).

	Port		**Starboard**	
Team	**Front**	**Rear**	**Front**	**Rear**
1	0.90 (0.055)	0.63(0.074)	0.85(0.100)	0.24(0.063)
2	00.80 (0.059)	0.69(0.063)	0.71(0.068)	0.55(0.065)

Table 3. Model Selection output from program MARK for a nested series of models that included variables for survey team, position in the aircraft, and side of the aircraft fitted to data from a survey of Dugong in the Torres Strait in 2001.

Model	No. Parameters	Deviance	AIC$_c$[a]	Delta AIC$_c$	AIC$_c$ Weight
Team·position·side	8	1418.7	428.8	0	0.987
Team·position	4	1435.6	437.5	8.6	0.013
Position	2	1449.8	447.7	18.9	0.000
Team	2	1486.4	484.3	55.4	0.000
Constant	1	1489.1	485.0	56.1	0.000

[a] AIC$_c$: Akaike's Information Criterion, corrected for small sample bias.

Our population estimates (Table 4) were based on probabilities of being available (Table 1) and probabilities of being detected given available (Table 2). The population size estimate from this analysis was 15.2% lower than from Marsh and Sinclair (1989a); differences were also evident at the level of survey block (Table 4). Precision using the new methodology (CV = 9.9 %) was better than precision of the previous methodology (CV = 16.4 %). In contrast, for the Northern Great Barrier Reef survey we obtained estimates of 9,855 for the new method and 9,193 for the old method, which was a somewhat smaller (7.2%) change and in the opposite direction. We also found the relative measurement error of the new method increased to CV = 12 % compared to CV = 10 % for the old method.

Table 4. Comparison of the population estimates (standard errors) of an aerial survey of the Torres Strait in 2001 using the methodology developed here to estimates using the methodology of Marsh and Sinclair (1989a).

	Marsh and Sinclair (1989a)		New Method	
Block	N	SE	N	SE
1a	685	317	635	94
1b	2,678	1,695	1,757	475
2a	3,504	403	3429	453
2b	583	166	440	83
3	5,473	1,327	4,927	972
4	1,183	655	778	150
Total	14,106	2,314	11,956	1,189

We also calculated estimates and standard errors using the synchronous cluster model. For the Torres Strait survey the mean group size was 1.3 dugongs and for Northern Great Barrier Reef survey the mean group size was 1.5 dugongs. The point estimates were unaffected, but the standard errors increased. For the Torres Strait the increase was from 9.9 % to 12.0 % while for the Northern Great Barrier Reef study the increase was from 12.0 % to 14.6 %.

DISCUSSION

Line Transects versus Strip Transects.—Often it may be preferable to use the line transect distance sampling approach extended to multiple observers (Alpizar and Pollock 1996, Manly et al. 1996, and Borchers et al.1998a, b), but we encountered difficulties that suggested that strip transects may be more appropriate for dugong surveys. Furthermore, there was no evidence of a decline in detection probability with distance, within our narrow strips. In addition, observers found it very difficult to accurately assign animals to distance classes due to cryptic surfacing behavior of dugongs and logistical difficulty of marking the boundaries of the distance classes within the transect. The sampling protocol based on independent observers precluded going back to look at sightings and measuring distance more accurately. Given the cryptic and brief (1-2 s) surfacing behavior of dugongs, it is impossible to relocate individual animals with certainty in turbid water. This is a serious problem as dugongs are usually seen individually or in very small groups (Marsh and Saalfeld 1989, Marsh et al. 1997a, 2004). Extensions of line transect methodology for multiple independent observers do not account for the problem of unavailable animals. Therefore, even if we had used the line transect methodology with multiple observers, our supplemental estimates of availability would still have been required. We do recommend, however, that distance data be collected in all transect surveys.

Availability Process.—We believe that the use of physical models to determine availability probabilities associated with spatially and/or temporally heterogeneous environments may have wide application in marine and terrestrial wildlife surveys. Anderson (2001) stated that many factors–including wind speed, temperature, time of sunrise, habitat type, season of year and its phenology, vegetation height and density, human disturbance, cloud cover, and sea state–have substantial effects on the number of animals detected. It is possible to reduce the variation in some of these influences by using standardized protocols and by setting strict ceilings on acceptable survey conditions. However, it is impossible to fully control for all variation. For example, in dugong surveys, water turbidity can change from clear-bottom-visible, to turbid, to clear-bottom-not-visible (Table 1) within a few minutes of aerial survey time, making it important to correct for availability at the scale of individual sightings.

Another solution to the problem of animals being unavailable for detection is tandem aerial surveys in which aerial observers are separated temporally by flying in different aircraft (e.g., Laake et al. 1997, Carretta et al. 1998, Hiby and Lovell 1998). A problem with this approach, in addition to high cost, is that the temporal separation makes it difficult to reliably determine which observations were made from both planes, plane 1 only, or plane 2 only. We consider the tandem aircraft option impractical for dugong surveys because of the impossibility of matching sightings, especially in turbid water.

Perception Process.—The use of the 2 independent observers on each side of the aircraft is essential for obtaining estimates of the probability of detection given availability. There is little additional cost of adding the second observer when compared to the cost of the aircraft hire, especially as twin-engine aircraft, often equipped with ≥6 seats, are mandatory for most offshore surveys in Australia. As a result of using curtains and an intercom system with tape recorders to visually and acoustically isolate tandem observers, we believe that the key assumptions are valid and biases minimal. Also, the estimates have reasonable precision and were quite consistent across observers in the earlier surveys. The later surveys exhibited more variation in these detection probabilities, probably because we used some less experienced observers. Recruiting or training a sufficient pool of experienced observers remains an important practical challenge.

Complications due to Clustering of Animals.— As our base model, we used a model clearly suitable for animals that occur singly but where the animals may be unavailable. Dealing with non- availability of animals is much more complex when animals occur in groups. Further there has been little or no research that we know of on the availability of grouped animals. We believe that the solutions will be situation-specific. For the dugong, we believe that the individual-based model is better because we had evidence that dugong surface independently and, also, because the group sizes were very small (mean 1.3 or 1.5). Furthermore, the protocol of not going off line and having a constant rapid speed should mean the availability of individuals in groups is not markedly increased over the availability of individuals occurring singly. In other surveys, when dugongs have occasionally been seen in groups of 10 or more, the aircraft has gone off line and attempted a census of the large group. Such groups have been treated as a separate stratum in the analysis (Marsh and Sinclair 1989a).

Comparison with Previous Approach.—The estimates obtained under our new methodology decreased markedly (15.3 %) for Torres Strait (Table 4). The estimates were more similar for the Northern Great Barrier Reef (9,855 versus 9,193), an increase of 7.2 %. Standard errors under our new methodology were similar to those obtained using the earlier methodology for Northern Great Barrier Reef survey (12 % versus 10 %) but for the Torres Strait survey the standard errors were much larger under the old method (9.9 % versus 16.4 %). The key point is that the new methodology is superior as the assumptions are more reasonable and more easily met in the field.

BENEFITS AND MANAGEMENT OUTCOMES

Aerial surveys using the standard techniques developed by Marsh and Sinclair (1989a, b) and extended here will continue to provide much of the information used to manage dugong populations in Australia. The capacity of aerial surveys of dugongs to detect trends is confounded by the tendency of dugongs to undertake large-scale movements between survey regions in response to stochastic diebacks of sea grass (Marsh et al. 1997a, Marsh and Lawler 2002). Therefore, requirements for dugong management are changing from detecting trends in abundance to identifying populations with levels of human-caused mortality that could lead to depletion s*ensu* Wade (1998). Estimates of absolute abundance will be critical for stock assessment, especially in regions such as Torres Strait that support substantial Indigenous dugong fisheries (Marsh et al. 1997a, 2004).

CONCLUSION

The absolute abundance estimates of dugongs in the Torres Strait and Northern Great Barrier Reef regions using the technique developed here indicate that the previous technique did not substantially underestimate the size of the dugong population as had been assumed (Marsh et al. 2002). Indeed the new method produced a smaller estimate (11,956 versus 14,106 dugongs) and a very much smaller standard error (1,189 versus 2,314 dugongs) for Torres Strait, whereas the new method produced slightly larger estimates (mean 9,855 versus 9,193 dugongs, standard error 1,184 versus 917 dugongs) for the Northern Great Barrier Reef survey. This research provides for the first time a robust method of the absolute abundance of dugongs as a basis for stock assessments using the PBR technique (Wade 1998).

REFERENCES

ALHO, J. M. 1990. Logistic Regression in Capture-Recapture Models, Biometrics 46:623-635.

ALPIZAR-JARA, R. 1997. Assessing assumption violations in line transect sampling. PhD Dissertation, Biomathematics Program, North Carolina State University, Raleigh, North Carolina, USA.

ALPIZAR-JARA, R. AND K. H. POLLOCK. 1996. A combination line transect and capture-recapture sampling model for multiple observers in aerial surveys. Ecological and Environmental Statistics 3:311-27.

ANDERSON, P. K. 1998. Shark Bay dugongs (*Dugong dugon*) in summer. II foragers in a *Halodule* dominated community. Mammalia 62:409-425.

ANDERSON, D. R. 2001. The need to get the basics right in wildlife field studies. Wildlife Society Bulletin 29:1294-1297.

BORCHERS, D. L., S. T. BUCKLAND, P. W. GOEDHART, E. D. CLARKE, AND S. L. HEDLEY. 1998a. Horvitz-Thompson estimators for double platform line transects. Biometrics 54:1221-37.

BORCHERS, D. L., W. ZUCCHINI, AND R. M. FEWSTER. 1998b. Mark-recapture models for line transect surveys. Biometrics 54:1207-20.

BUCKLAND, S. T., D. R. ANDERSON, K. P. BURNHAM, J. L. LAAKE, D. L. BORCHERS, AND L. THOMAS. (2001). Introduction to distance sampling. Oxford University Press, Oxford.

BURNHAM, K. P., AND D. R. ANDERSON. 1976. Mathematical models for non-parametric inferences from line transect data. Biometrics 32:325-336.

___________, AND __________. 1998. Model selection and inference: A practical information theoretic approach. Springer-Verlag, New York.

CARETTA, J. V., K. A. FORNEY, AND J. L. LAAKE. 1998. Abundance of California coastal bottlenose dolphins estimated from tandem aerial surveys. Marine Mammal Science 14:655-675.

CAUGHLEY, G. 1977. Analysis of vertebrate populations. Wiley, New York.

_________, AND D. Grice. 1982. A correction factor for counting emus from the air, and its application to counts in Western Australia. Australian Wildlife Research 9:253-259.

_________, AND G. C. Grigg. 1981. Surveys of the distribution and density of kangaroos in the pastoral zone in South Australia, and their bearing on the feasibility of aerial survey in large remote areas. Australian Wildlife Research 8:1-11.

CHEN, S. X., AND A. COWLING. 2001. Measurement Errors in Line Transect Surveys where Detection varies with Distance and Size. Biometrics 57:732-742.

CHILVERS, B. L., S. DELEAN, N. J. GALES, D. K. HOLLY, I. R. LAWLER, H. MARSH, AND A. R. PREEN. 2004. Diving behaviour of dugongs. Journal of Experimental Marine Biology and Ecology: 304: 203-224

COOK, R. D., AND J. O. JACOBSEN. 1979. A design for estimating visibility bias in aerial surveys, Biometrics 35:735-742.

GRIER, J. W., J. M. GERRARD, G. D. HAMILTON, AND P. A. GRAY. 1981. Aerial visibility bias and survey techniques for nesting bald eagles in northwestern Ontario. Journal of Wildlife Management 45:83-92.

HAIN, J. H. W., S. L. ELLIS, R. D. KENNEY, AND C. K. SLAY. 1999. Sightability of right whales in coastal waters of the southeastern United States with implications for the aerial monitoring program. Pages 191-207 *in* G. W. Garner, S. C. Amstrup, J. L. Laake, B. F. J. Manly, L. L. McDonald, and D. G. Robertson editors. Marine Mammal Survey and Assessment Methods. Balkema, Rotterdam.

HEINSOHN, R., R. C. LACY, D. B. LINDENMAYER, H. MARSH, D. KWAN, AND I. LAWLER. 2004. Unsustainable harvest of dugongs in Torres Strait and Cape York (Australia) waters: two case studies using population viability analysis. Animal Conservation 7: 417-425.

HIBY, A. R., AND P. LOVELL. 1998. Using aircraft in tandem formation to estimate abundance of harbour porpoise. Biometrics 54:1280-89.

HOLT, R. S., AND J. E. POWERS. 1982. Abundance estimation of dolphin stocks in the eastern tropical pacific yellowfin tuna fishery determined from aerial and ship surveys to 1979, United States Department of Commerce, NOAA Technical Memorandum NOAA-TM-NMFS-SWFC-23.

HUGGINS, R. M. 1989. On the statistical analysis of capture experiments. Biometrika 76:133-40.

_________, 1991. Some practical aspects of a conditional likelihood approach to capture experiments. Biometrics 47:725-32.

JOHNSON, F. A., K. H. POLLOCK, AND F. MONTALBANO. 1989. Visibility bias in aerial surveys of mottled ducks. Wildlife Society Bulletin 17:222-227.

JOLLY, G. M. 1969. Sampling methods for aerial census of wildlife populations. East Africa Agriculture and Forestry Journal 34:46-49.

LAAKE, J. L., J. C. CALAMBBOKIDIS, S. D. OSMEK, AND D. J. RUGH. 1997. Probability of detecting harbour porpoise from aerial surveys: estimating *g*(0). Journal of Wildlife Management 61:63-75.

MANLY, B. F. J, L. L. MCDONALD, AND G. W. GARNER. 1996. Maximum likelihood estimation for the double count method with independent observers. Journal of Agricultural, Biological, and Environmental Statistics 1:170-189.

MARSH, H. 2000. Evaluating management initiatives aimed at reducing the mortality of dugongs in gill nets in the Great Barrier Reef World Heritage Area. Marine Mammal Science 16:684-94.

_________, AND I. LAWLER. 2002. Dugong distribution and abundance in the northern Great Barrier Reef Marine Park November 2000. Great Barrier Reef Marine Park Authority Research Publication 77.

_________, AND G. B. RATHBUN. 1990. Development and application of conventional and satellite radio -tracking techniques for studying dugong movements and habitat usage. Australian Wildlife Research 17:83-100.

_________, AND W. K. SAALFELD. 1989. The distribution and abundance of dugongs in the northern Great Barrier Reef Marine Park. Australian Wildlife Research 16: 429-440.

_________, AND D. F. SINCLAIR. 1989a. Correcting for visibility bias in strip transect aerial surveys of aquatic fauna. Journal of Wildlife Management 53:1017-24.

_________, AND _________. 1989b. An experimental evaluation of dugong and sea turtle aerial survey techniques. Australian Wildlife Research 16:639-650.

_________, A. N. M. HARRIS, AND I. R. LAWLER.1997a. The sustainability of the Indigenous dugong fishery in Torres Strait, Australia/ Papua New Guinea. Conservation Biology 11:1375-1386.

_________, P. CORKERON, N. MORISSETTE, AND A. R. PREEN. 1997b. An assessment of the sustainability of the Indigenous dugong fishery in Torres Strait. Unpublished Report to Australian Fisheries Management Authority.

_________, H. PENROSE, C. EROS, AND J. HUGUES. 2002. Dugong status report and action plans for countries and territories. UNEP Early Warning and Assessment Report Series 1.

MARSH, H., I. R. LAWLER, D. KWAN, S. DELEAN, K. POLLOCK, AND M. ALLDREDGE. 2004. Aerial surveys and the potential biological removal technique indicate the Torres

Strait dugong fishery is unsustainable. Animal Conservation 7: 435-443.

MARSH, H. G. DE'ATH, N.GRIBBLE AND B. LANE. in press. Historical marine population estimates: triggers or targets for conservation? The dugong case study. Ecological Applications.

PEEL, M. J. S., AND J. D. BOTHMA. 1995. Comparison of the accuracy of four methods commonly used to count impala. South African Journal of Wildlife Research 25:41-43.

POLLOCK, K. H., AND W. L. KENDALL. 1987. Visibility bias in aerial surveys: A review of estimation procedures. Journal of Wildlife Management 51:502-510.

PREEN, A. R. 1989. The status and conservation of dugongs in the Arabian Region. MEPA Coastal and Marine Management Series, Saudi Arabia. Technical Report, Dugongs, Volume 1.

RESTREPO, V. R., J. M. HOENIG, J. E. POWERS, J. W. BAIRD, AND S. C. TURNER. 1992. A simple approach to risk and cost analysis, with applications to swordfish and cod fisheries. Fisheries Bulletin. 90:736-748.

RICE, W. R., AND J. D. HARDER. 1977. Application of multiple aerial sampling to a mark-recapture census of white-tailed deer. Journal of Wildlife Management. 42:197-206.

SEBER, G. A. F. 1982. The estimation of animal abundance and related parameters (2nd ed.), Charles W. Griffin, London, UK.

THOMPSON, S. K. 2002. Sampling (2nd ed.), Wiley, New York, USA.

WADE, P. R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnepeds. Marine Mammal Science 14:1-37.

WHITE, G. C., AND K. P. BURNHAM. 1999. Program MARK: Survival Estimation from Populations of Marked Animals, Bird Study 46:120-139.

_________, R. M. BARTMANN, L. H. CARPENTER, AND R. A. GARROTT.1989. Evaluation of aerial line transects for estimating mule deer densities. Journal of Wildlife Management 53:625-635.

WRIGHT, I. E., J. E. REYNOLDS, B. B. ACKERMANN, L. I. WARD, B. L. WEIGLE, AND W. A. SZELISTOWSKI. 2002. Trends in manatee (*Trichechus manatus latirostris*) counts and habitat use in Tampa Bay 1987-1994: Implications for conservation. Marine Mammal Science 18:259-274.