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Bias in manta tow surveys of *Acanthaster planci*

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Abstract. To investigate the biases associated with manta tow surveys of *Acanthaster planci,* counts obtained by manta-towed observers were compared with counts made on SCUBA swims under a limited range of conditions. Five 10 m wide strip transects on different parts of two reefs and with different densities of *A. planci* were surveyed. On average, 22.7% of starfish counted on SCUBA searches were counted on manta tows over the same transect (SD = 12.0%, $n = 69$). This proportion is termed sightability. As sightability decreases with increasing transect width, we estimate that, on average, less than 5% of the *A. planci* present are counted on routine manta tows which are conducted over transect of undefined width. Multiple regression analysis was used to determine which of 33 variables explained most of the variation in sightability in 10 m wide transects. The most influential variables were the proportion of cryptic starfish and an index of the degree of reef complexity. A regression equation designed to improve estimates of the abundance of *A. planci* on routine manta tows was developed. However, as it explained only 39% of the variation in sightability, this equation is of limited value in stabilising the negative bias associated with manta tow counts. In view of the variability of this bias, the manta tow technique is not suitable for estimating absolute densities of *A. planci.* Manta tow surveys are appropriate for identifying gross relative differences between densities of *A. planci,* and thus for determining broad-scale patterns of abundance. As such, they are a cost-effective method of estimating the geographical extent of *A. planci* outbreaks.

Introduction

Manta tow surveys, conducted by towing snorkel divers behind a boat, have been used for rapidly surveying reefs since the early 1970's (Goreau et al. 1972; Kenchington and Morton 1976; Done 1982). The technique is frequently used to monitor gross, broadscale changes in the abundance and distribution of *Acanthaster planci* (Kenchington and Morton 1976; Moran et al. 1988; Johnson et al. 1988). Manta towing is considered appropriate for this purpose as *A. planci* seldom occurs in intermediate densities and their abundance usually changes quite rapidly (Moran 1986; Moran et al. 1988). However, as acknowledged by advocates of the technique, manta tow counts may be biased and imprecise.

Marsh and Sinclair (1989) point out that the visibility bias associated with rapid survey techniques typically consists of both perception bias (which occurs when potentially visible target organisms are missed by observers) and availability bias (which occurs when target organisms are unavailable to observers due to viewing conditions). It is important to know the magnitude and variation of the biases associated with the manta tow technique in order to evaluate the reliability of the surveys for *A. planci.*

Kenchington and Morton (1976) and Moran and Sinclair (unpublished) have compared estimates of the abundance of *A. planci* using manta tows and swim searches of the same general area in attempts to measure the perception bias. However, as the sampling areas covered by the manta tows were not known exactly, it was not possible to quantify this bias. Furthermore, no account was taken of the availability bias.

The manta tow technique may be regarded as the marine analogue of an aerial survey for wildlife, another rapid survey technique (Done et al. 1981). There is a relatively large literature on improvements to aerial survey methodology including attempts to quantify biases (e.g. Caughley et al. 1976; Samuel et al. 1987; Marsh and Sinclair 1989). This paper is the first detailed attempt to make similar improvements in the manta tow technique.

Methods

Five study sites with a range of densities of *A. planci,* (4 at Bowden Reef; 1 at Shell Reef, termed "main transects") were chosen for

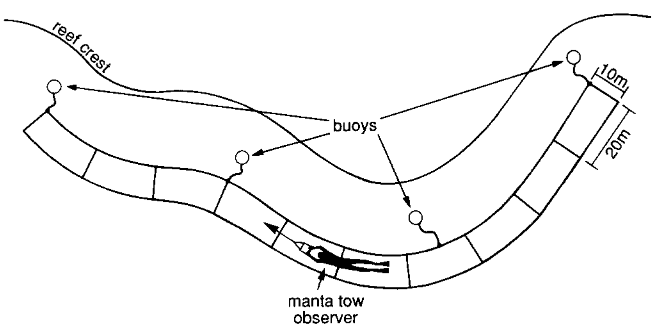

Fig. 1. Diagram of a representative transect illustrating the position in relation to the reef and manta tow observer who is towed at 4.96 km h^{-1} ($n=67$, SD$=0.74$). The transect was defined by ropes placed along the substrate of the reef slope and buoys at the surface

comparing counts of *A. planci* obtained on manta tows and SCUBA swims. During pilot investigations, data were collected from three other reefs (Davies, Centipede and Old) with low numbers of starfish. All sites were in the central Great Barrier Reef (approximately 148° E and 19° S).

Our manta tow technique was based on that used in routine surveys by the Australian Institute of Marine Science (AIMS) (Bass et al. 1988; Moran et al. 1988). All observers had about 4 years experience as members of the AIMS manta tow team. *A. planci* were counted by one or two snorkel divers towed behind a dinghy on individual manta boards at about 5 km h^{-1} (Fig. 1). After each 200 m long tow, the observer recorded data on a pro forma attached to the board. On AIMS surveys each area is searched only once until the entire perimeter of a reef is surveyed, but in this study each observer was towed in the same direction over each transect three times within 15 min (triplicate tow). The width of the search path is not defined on the AIMS surveys and the observer typically scans the entire reef slope. In contrast, our observers searched for *A. planci* within a transect (Fig. 1). Ropes defined the area searched by the manta-towed observer while buoys guided the boat driver along the transect. Except at Shell Reef, each transect was 200 m long and 10 m wide, and was divided into ten 20 m long lanes running across the slope (Fig. 1). The transect at Shell Reef was 220 m long (11 lanes).

Within 30 min of each triplicate tow, SCUBA divers systematically searched each 20 m × 10 m lane in the transect counting *A. planci*. Animals found in concealed or protected locations were classified as cryptic. These data enabled us to calculate the following for the starfish in each transect: sightability (the starfish counted on manta tows as a proportion of those counted on SCUBA searches); mean density per lane; degree of aggregation (variance to mean ratio of the counts per lane); and the proportion cryptic. The inability of manta tow observers to count small starfish was not considered a factor in the analysis as only 17 of approximately five thousand starfish counted on SCUBA searches were less than 20 cm in diameter.

Divers recorded physical characteristics of each transect (Table 1) and survey conditions (Table 2). Visibility was estimated using transect ropes at known distances. The average depth and slope of each transect was estimated by taking approximately 55 depth readings along the ropes defining the lanes of each transect (Fig. 1). Fernandes classified 400 randomly determined points in each transect into three categories (+, −, ?) on the basis of the likelihood of *A. planci* being hidden from a manta-towed observer at that point.

Analysis

A forward stepwise multiple linear regression (Snedecor and Cochran 1980), which maximised the co-efficient of determination (r^2) at each step, was used to determine which of the factors explained most of the variability in the sightability of *A. planci*. These factors included those (a) listed in Tables 1 and 2, and (b) describing the abundance and behaviour of the starfish (density, aggregation and proportion cryptic). Samuel et al. (1987) suggest that this univariate approach, which fails to consider interactions between independent variables, could lead to over-estimation of the number of factors influencing visibility bias. In view of their concern and the large number of independent variables (Tables 1 and 2), we used a relatively conservative F-to-enter value of 6 as the cut-off point in the regressions. The regression was repeated using the subset of variables which could be readily recorded or controlled on a routine manta tow survey. An arc sine transformation was applied to dependent variables with binomial distributions. Nominal variables were analyzed as dummy variables (Zar 1984).

Table 1. Parameters describing the physical characteristics of each transect and used in the regression analyses. Those underlined were significant in at least one of the three analyses. N = nominal; I = interval; R = ratio; CV = coefficient of variation

Variable (data type)	Categories actually recorded/range
Every transect	
Reef (N)	
Site (N)	
Average depth (R)	2.6–8.4
CV depth (R)	0.3–0.8
Average slope (I)	14–42°
CV of slope (R)	0.8–1.8
Coral community type[a] (N)	Staghorn thickets, mixed coral, plate coral
Reef zone[a] (N)	*Windward*, leeward, flank
Topography[a] (N)	Evenly sloping to base 10–70°, *broken up and irregular*, canyons undulating bottom, vertical slope
Structural complexity (N)	High-staghorn thickets and/or broken topography, medium-mixed communities with canyons or vertical walls, low-mixed or plate communities and even slopes
Main transects[b]	
No. of 400 points in each transect in each category	+ *A. planci* definitely obscured/44–225; − *A. planci* not obscured/105–307, *? A. planci may be obscured from a manta-towed observer/46–90*

[a] Based on P. Moran (unpublished data 1988)
[b] See Methods for definition

Table 2. Variables recorded when manta towing. Those underlined were significant in at least one of the regressions. N = nominal; O = ordinal; I = interval; R = ratio

Variable (data type)	Categories actually recorded/range
Per triplicate tow	
Season (N)	Summer, *autumn*, winter, spring
24 h time (I)	0730–1650
Time from sunrise (R)	1.7–10.5 h
Time to sunset (R)	1.5–11.2 h
Underwater visibility (O)	6–12 m, 12–18 m, >18 m
Cloud cover (O)	0–8 oktas
Wind (O)	<10 kn, 10–20 kn, >20 kn
Wave height (O)	<0.5 m, 0.5–1.5 m, >1.5 m
Current (N)	None, towing with or into current
Sun (N)	Towing into sun or *not*
Tide (N)	*slack*, ebb, flood
Depth of water (R)	0.2–2.8 m above datum
Per tow	
Observer (N)	
Boat driver (N)	
Duration (R)	90–185 s
Replicate number (R)	1, 2 or 3
Number of previous tows per day per observer (R)	0–14
Per observer per tow[a]	
Number of *A. planci* (R)	0–314
Average size *A. planci* (O)	<15 cm, 15–35 cm, >35 cm
Live coral cover (O)	1–10%, 11–30%, 31–50%
Dead coral cover (O)	0%, 1–10%, 11–30%, 31–50%, 51–75%
Soft coral cover (O)	0%, 1–10%, 11–30%
Sand and rubble cover (O)	0%, 1–10%, 11–30%
Feeding scars[b] (O)	0, 1–10, >10

[a] Values of these variables are routinely recorded by members of the AIMS manta tow team and were recorded in this experiment to maximise similarity to standard surveys. The 'number of *A. planci*' was the only one of these variables used in the analyses
[b] Small conspicuous patches of dead coral caused by feeding *A. planci*

Validation of the methods

Effect of driver

If the boat driver remained constant, the number of *A. planci* counted per tow tended to increase within a triplicate tow. However, the counts did not increase if the driver changed (Table 3), suggesting that at least part of the increase resulted from the driver's learning to drive over the transect, rather than the observer's learning the locations of starfish. In routine manta tows, the driver is not required to pass over a specific section of reef, and thus driver learning does not affect sightability of *A. planci*. As the driver was most likely to position the observer correctly on the third tow of each triplicate, only the data from this tow were used in the analysis to minimize the impact of the confounding effect of driver learning on the results.

Table 3. Results of paired *t*-tests analyzing differences between counts of *A. planci* made on consecutive tows within each triplicate. The data were log (base 10) transformed to reduce the heteroscedasticity

Repeat numbers compared	Mean difference (counts per tow)	*df*	*t*	*P*
One driver per triplicate				
Tow 2–tow 1	0.2938	54	3.5241	0.0009
Tow 3–tow 2	0.0904	54	1.6327	0.1082
Tow 3–tow 1	0.3842	54	4.7021	0.0001
Drivers change within triplicate				
Tow 2–tow 1	0.1191	14	0.8862	0.3895
Tow 3–tow 2	0.0866	14	1.1929	0.2514
Tow 3–tow 1	0.2057	14	1.5737	0.1364

Differences between manta-towed observers

There was no significant difference between the sightability of starfish for observers towed singly and in tandem (*t*-test: $df = 67$, $t = 1.187$, $P = 0.3368$). However, estimates of starfish numbers differed significantly within tandem observer teams (paired *t*-test: $df = 15$, $t = 3.938$, $P = 0.0013$) indicating that it was important to include observer as a factor in the analyses.

Differences between SCUBA divers

The effects of individual divers and of small scale temporal variation on the precision of SCUBA counts of *A. planci* were investigated over several field trips using several divers simultaneously. A starting lane within each transect was randomly allocated to each diver who then searched two to four adjacent lanes depending on the manpower available. Summing individual counts of the different lanes of the transect provided an estimate of starfish numbers in the whole transect. Within the same dive, divers were then rotated systematically between lanes until each lane was counted independently by three different divers. Count variability was investigated by comparing the average of the three consecutive counts of the same lane with the initial count. There was no significant difference between these values indicating that there was no significant small scale temporal variation in SCUBA counts (paired *t*-test: *df*=148, *t*=1.120, *P*=0.256). As the consecutive searches of lanes were conducted by different SCUBA divers, the above test also showed that individual differences between SCUBA divers could be ignored in the analyses.

Double counting on SCUBA swims

SCUBA divers counted the number of *A.planci* per lane without marking them and then repeated the count marking each animal with a cut. No difference was detected between the numbers of marked and unmarked starfish indicating that little double counting was occurring (paired *t*-test: *df*=2, *t*=0.500, *P*=0.667). Sites at which starfish were marked were not used in subsequent investigations.

Accuracy of SCUBA counts

A perception bias averaging 11.28% (*n*=7, SD=4.51) in SCUBA counts of *A.planci* was detected as a significant number of starfish were missed by SCUBA search (onetailed paired *t*-test: *df*=6, *t*=5.303, 0.001 > P > 0.0005). This was assessed when one diver marked *A.planci* in several lanes while counting and another diver followed immediately counting only unmarked starfish. This underestimation is compounded by availability bias, as not all cryptic starfish are available for divers. Further subdivision of lanes (into 2 × 20 m or 3 × 20 m blocks) did not improve the accuracy of the SCUBA counts (paired *t*-test: *df*=2, *t*=0.000, *P*=1.000).

Problems of definition

A significant proportion of the observed variation in the proportion of cryptic starfish between divers within transects was due to difficulties in unambiguously defining "cryptic" (nested anova: subsample = observer, *df*=10 × 264, *F*=7.112, *P*<0.01). However, this observer bias accounted for only approximately 3.5% of the total variability in the proportion of cryptic *A.planci.* In contrast, 71% of variation depended on the population of starfish sampled. The proportion of cryptic starfish was therefore validly included in the analyses.

Results

Estimates by SCUBA divers of the density of *A.planci* per transect ranged from 0.002 to 0.487 starfish m^{-2}. The degree of aggregation per transect ranged from 0.78 to 42.06. The proportion of starfish in a transect that was classified as cryptic averaged 39.75% (SD=18.13; range 7–86%, *n*=45). The ranges of the other variables are listed in Tables 1 and 2.

Variables affecting the manta tow counts

Between 0 and 57% (average=22.7%) of the *A.planci* counted on SCUBA swims were counted on manta tows (*n*=69, SD=12.0). A regression of sightability on the variables describing the abundance and behaviour of the starfish plus those listed in Tables 1 and 2, includes six significant variables [Eq. (1)] which explain 71% of the variation in the response (ANOVA of regression: error *df*=59, *F*=23.81, *P*=0.0001; Table 4).

$$\begin{aligned}\text{Sightability} = {} & 0.460 - 0.482\,(\text{proportion cryptic}) \\ & - 0.004\,(\text{may obscure}) + 0.065\,(\textit{visibility}) \\ & + 0.150\,(\text{Observer D}) - 0.089\,(\textit{slack tide}) \\ & + 0.072\,(\textit{no sun})\,. \qquad (1)\end{aligned}$$

Equation (1) indicates that the sightability of *A.planci* was negatively correlated with the number of cryptic starfish and the topographical complexity of the site (of which the variable 'may obscure' is an index). In contrast, sightability was positively correlated with underwater visibility. Sightability was also greater for one of the observers than the others and when the boat driver did not steer into the sun. However, sightability was less at slack tide.

It would be feasible to record only three of these six variables [in italics in Eq. (1)] on regular manta tow surveys. Equation (2), which indicates that the sightability of *A.planci* was greatest on the windward side of reefs and positively correlated with underwater visibility, is of more practical value as the analysis included only variables which can be readily recorded on routine surveys. However, it is much less satisfactory than Eq. (1) as it explains only 39% of the variation in the sightability of *A.planci* (ANOVA of regression: error *df*=65, *F*=20.46, *P*=0.0001; Table 4).

$$\begin{aligned}\text{Sightability} = {} & 0.087 + 0.097\,(\text{windward side}) \\ & + 0.051\,(\text{visibility})\,. \qquad (2)\end{aligned}$$

Table 4. Variables which explained a significant amount of the variation in the sightability of *A. planci.* Results of multiple stepwise regressions on (1) all the variables measured and on (2) the subset of variables which are readily recorded on routine surveys

Variable	Parameter estimate	SE	*F*	*P*
(1) *Regression model including all variables*				
$r^2=0.7077$				
Intercept	0.4604	0.0665	47.88	0.0001
Proportion cryptic	−0.4824	0.0569	71.98	0.0001
May obscure	−0.0037	0.0006	37.63	0.0001
Visibility	0.0649	0.0121	28.82	0.0001
Observer D	0.1495	0.0375	15.90	0.0002
Slack tide	−0.0889	0.0287	9.60	0.0030
No sun	0.0723	0.0278	6.78	0.0116
(2) *Regression model on readily measured variables*				
$r^2=0.3864$				
Intercept	0.0873	0.0320	7.47	0.0081
Windward zone	0.0972	0.0279	12.15	0.0009
Visibility	0.0507	0.0163	9.63	0.0028

Table 5. Variables which explained a significant amount of the variation in the proportion of *A. planci* that are classified as cryptic. Results of multiple stepwise regressions on all variables ($r^2=0.7013$)

Variable	Parameter estimate	SE	*F*	*P*
Intercept	0.2280	0.0623	13.37	0.0005
Flood tide	0.2350	0.0383	37.60	0.0001
Site B	0.1968	0.0443	19.73	0.0001
Broken topog.	−0.1194	0.0395	9.14	0.0036
Cloud	0.0249	0.0085	8.50	0.0050
Time to sunset	0.0142	0.0055	6.80	0.0115
Autumn	−0.1420	0.0579	6.02	0.0170

The proporiton of cryptic starfish was the most important influence on the sightability of *A.planci*. Most of the variability in this factor was attributable to flood tides and a leeward reef site (ANOVA of regression: error $df=61$, $F=23.87$, $P=0.0001$; Table 5).

Discussion

The extent and variability of the bias in manta tow counts of A. planci

A. planci are significantly undercounted on manta tow surveys. On average, 22.7±12% (SD) of the starfish counted on SCUBA swims were counted on our manta tows which were conducted over a 10 m wide transect. The negative bias which occurs on routine manta tow surveys in which the transect width is undefined could be substantially greater than this. Fernandes (1990a) showed that about four times as many artificial targets (similar to *A.planci* in size and coloration) were counted in a transect 9 m wide than in the 30 m transect designed to simulate the effective transect width in routine surveys. In addition, our data show that starfish can be undercounted by SCUBA divers by 11.3% plus an unknown (and probably variable) proportion of cryptic starfish which are unavailable to observers on SCUBA. Taken together, these results suggest that, on average, manta-towed observers will count less than 5% of the *A.planci* present in the area searched on routine surveys.

Our data also indicate that the number of starfish counted on a manta tow is a very variable index of the number of *A.planci* present. The degree of undercounting was significantly affected by a number of factors including the proportion of starfish that are cryptic, the topographical complexity of the site, underwater visibility, the observer, whether or not the boat driver was steering into the sun, and the state of the tide. Although the effects of the density and degreeof aggregation of targets were not identified in this study as sources of bias in manta tow surveys of *A.planci,* this may partly have been due to density being confounded with reef zone. "Very high densities" were recorded only on one windward reef site probably influencing our results which suggest that the sightability of *A.planci* was greatest on the windward side of reefs. Degree of aggregation was positively correlated with density (Fernandes 1990b) and therefore also confounded with reef zone. Kenchington and Morton (1976) and Done (1982) indicated that these factors can be additional sources of significant variation in manta tow counts of *A.planci*, and Fernandes (1990a) showed that the sightability of artificial targets designed to simulate *A.planci* was greatest when they were at high densities and aggregated in large groups.

Although our data suggest that the variability in the bias can be partially corrected using regression equations, less than half of this variability was explained by factors which are feasible to measure or control during routine surveys. This result suggests that attempts to use this approach to estimate accurately the density of starfish present would have limited success. However, regression Eq. (2) could be used to improve manta tow estimates of *A.planci* by partially stabilizing the bias under the variable conditions inevitably encountered in large scale surveys. If it is decided to use this approach, refinement of the regression by increasing the database on which it is based is essential and should concentrate on collecting data on variables which can be monitored on routine surveys. The present database is particularly limited with regard to number of sites and reefs sampled. In addition, more data should be collected on the conditions influencing the proportion of *A.planci* which are available to observers (see Fernandes 1990b).

Future use of manta tows for A.planci

The manta tow technique obviously cannot provide accurate estimates of the absolute number of starfish. However, if information on the broad-scale distribution of outbreaks of *A.planci* (sensu Moran 1986) over vast areas (such as the Great Barrier Reef) is required, then the manta tow technique is presently the only logistically feasible means of collecting these data.

This research suggests that if manta tow surveys of *A.planci* are to continue, the technique should be improved. This is already being done by the AIMS manta tow team (Moran et al., 1989). The zone of the reef and the visibility should be recorded and the information used in regression equations to reduce the variability of bias associated with estimates of the abundance of *A.planci.* Towing should be organised so that boat drivers have the sun behind them whenever possible. Only experienced observers should be used. The relative differences between observers should be estimated during regular surveys by towing each observer over 5–10 areas where starfish are present and the differences incorporated into the regression equations.

As currently used, the manta tow can identify reefs with extremely large aggregations or extremely low densities of *A.planci.* If a more detailed categorization of reefs is required, with respect to starfish densities, a robust classification scheme, which takes the limitations of the manta tow technique into account, needs to be developed concurrently with improvements in the field technique.

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