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What do you mean "There's an outbreak of crown-of-thorns starfish on the Great Barrier Reef."?

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Introduction

Large aggregations of the crown-of-thorns starfish (*Acanthaster planci*) have caused extensive coral mortality in reef systems in Australia as well as around the Indo-Pacific region (Moran 1986). Such population aggregations have long been labelled "outbreaks", (Chesher 1969). The term "outbreak" has been defined based mainly upon the criterion of population density or size (Pearson and Garrett 1976). However, many workers recognise the inadequacy of a single criterion upon which to identify an outbreak (Moran 1986, Keesing and Lucas 1992, Moran and Death 1992b). Since 1985, the Australian Institute of Marine Science (AIMS) has used more comprehensive criteria in an informal decision-making process classifying outbreak and non-outbreak populations of crown-of-thorns starfish (Moran et al 1988). Extensive research has since been conducted, and management decisions made, in Australia based on outbreaks of starfish as defined by experts at AIMS (Birkeland and Lucas 1990).

Biological classification schemes which distinguish the threshold between outbreak and non-outbreak populations of crown-of-thorns starfish have received little attention (Moran 1986). This is partially due to a dearth of comparative data on non-outbreaking populations of the species in question (Birkeland and Lucas 1990). Outbreaks also vary spatially and temporally (Dana *et al.* 1972, Moran 1986, Reichelt *et al.* 1989, Moran and De'ath 1992). Although the biological definition remains elusive, working definitions of outbreaks have been developed and used for summarising the distribution and status of different starfish populations.

To date, the working definitions of crown-of-thorns starfish outbreaks have been many, ambiguous and/or limited. For example, Chesher (1969) provided seven different and inconsistent descriptions of normal versus outbreak populations of crown-of-thorns starfish (Dana *et al.* 1972). Bass *et al.* (1989a), Bass *et al.* (1989b) and Baker *et al.* (1990) defined an outbreak somewhat ambiguously: "large numbers of starfish (generally greater than 40 per reef) and extensive hard coral mortality". The meaning of "extensive" was not clarified, the size of reef was not considered and sometimes the threshold of 40 was not applied. Other workers have specified a number of crown-of-thorns starfish per unit area even though the techniques used did not sample any measured area (Pearson and Endean 1969, Dana *et al.* 1972). Recently, Moran and De'ath (1992b) suggested that average counts of 0.22 starfish per manta tow (covering roughly a 200m long by 10m wide area) on a reef may be indicative of an outbreak. They also noted that the abundance of starfish per se is not necessarily a reliable indicator of an outbreak (Moran and De'ath 1992b).

Despite these problems, descriptions of the distribution and abundance of outbreaks of crown-of-thorns starfish, and other outbreaking species, are used to inform managers as well as the general public and government agencies (Great Barrier Reef Marine Park Authority 1984, Great Barrier Reef Marine Park Authority 1985). Researchers also use the data to identify the pattern of outbreaks and to direct further studies aimed at understanding the phenomenon (Moran *et al.* 1988; Dight *et al.* 1990; Reichelt *et al.* 1990, Moran *et al.* 1992). It is important that the working definition of outbreak be made transparent, rigorous and repeatable. The present research fulfils this need.

We developed a system for classifying reefs on the Great Barrier Reef (GBR), Australia, in terms of the population status of *Acanthaster planci*. This paper documents and formalises the expert-opinion based classification system used by the AIMS for almost a decade. As such, it introduces transparency to the term "outbreak" as used in the substantial amounts of work on the phenomenon in Australia.

Methods: defining the basis for the decision criteria

Data used

We used information from reefs surveyed by the AIMS Crown-of-thorns Study Broadscale Survey team using the manta tow technique (Baker *et al.* 1991). This technique involves towing snorkel divers behind a dinghy around the perimeter of each reef. During each two minute tow a snorkeller visually records information on crown-of-thorns starfish abundance and coral cover (Moran *et al.* 1989). These data have been used, informally, for many years to determine the status of reefs with regard to starfish outbreaks on the GBR (Moran *et al.* 1988).

All data from complete, standard AIMS manta tows collected between 1985 and 1990 were used in the formalisation of the decision process and generation of Table 1 (622 records). Details of the manta tow method are described in Moran *et al.* (1989).

Reef classification with regard to outbreaks of crown-of-thorns starfish

The categories of reef classification which AIMS have used are:

Active outbreak (AO) = the reef is supporting an active outbreak of starfish. This category indicates relatively large numbers of starfish causing extensive hard coral mortality;

Recovering (RE) = the reef is recovering from an outbreak. This refers to post-outbreak reefs where extensive areas of dead hard coral remain and possibly above normal numbers of residual starfish; and

No outbreak (NO) = the reef shows no evidence of an outbreak (Bass *et al.* 1989a; Baker *et al.* 1990).

We retained these categories as the classification alternatives as they satisfy the needs of the users of the data (e.g. managers, public, scientists) and provide for consistency. One aim is to clarify the ambiguity of the adjectives used in the definitions (e.g. relatively large, extensive).

Criteria by which crown-of-thorns starfish surveys of reefs are categorised

Since 1985, AIMS used several criteria informally to identify outbreaks populations of starfish: the number of starfish in relation to the size of the reef; total number of *A. planci* per reef; estimates of live and dead coral cover; and the degree of aggregation of crown-of-thorns starfish. We retain these criteria but used statistical estimates to formalise the population parameters:

1) the mean number of starfish per manta tow is used as an index of the total number of starfish on a reef in relation to the size of the whole reef and

2) on each reef the variance to mean ratio (VMR) of the number of crown-of-thorns starfish per manta tow is used as an index of the degree of aggregation of starfish on the reef.

Data on live coral cover and dead coral cover was recorded by manta towed observers within the following levels:

Level	Percentage cover
0	0
1	1-10
2	11-30
3	31-50
4	51-75
5	76-100

These levels were used directly within the formalised decision key. Definitions of live and dead coral cover are provided in Moran *et al* (1989) and Fernandes (1991).

Determining threshold values of the decision criteria

Classification of reefs with regard to outbreaks depends upon the crown-of-thorns population size and coral cover. The levels at which one distinguishes between one classification and another is by application of "threshold" values.

Of the total data used to define thresholds of the decision criteria, 134 records had been classified, using the informal assessment process, as AO reefs, 240 as RE reefs (of which 58 had counts of *A. planci*) and 248 as NO reefs (of which 123 had counts of *A. planci*). Investigation of the level of each of the decision criteria within each category of "outbreak" status enabled us to formally identify and define the decision criteria which had been used. For

example, we found that all of the reefs labelled as active outbreak averaged more than 0.5 crown-of-thorns starfish per manta tow. Thus, 0.5 crown-of-thorns starfish per manta tow on a reef became one of the thresholds of the decision criteria in the decision key. Other thresholds were developed similarly. The decision criteria and thresholds were organised in the form of a key and adjusted until they matched both the process used by the expert (project leader and second author) and the recorded classifications.

Some discrepancies were noted between the formalised decision criteria developed and the actual classification of reefs. For example, one reef with a count of no crown-of-thorns starfish was labelled as an outbreaking reef due to data collected on SCUBA by the AIMS Broadscale Survey team during that same field trip. Consequently, where external data sources influenced the categorisation of a reef, explicit reference to those sources is required in the decision key.

Distinguishing between reefs which should be categorised as recovering versus categorised as having no current evidence of an outbreak can be difficult. Previous surveys of reefs can indicate whether that reef has suffered from an outbreak or not. If this data is not available, one can compare the live and dead coral status and crown-of-thorns starfish populations with “no outbreak” reefs in the same sector of the GBR and cross shelf position (inner, mid and outer shelf (Table 1). If the reef in question has more starfish and dead coral and less live coral that the “no outbreak” reefs, for example, then it would be classified as a recovering reef. The sectors and cross shelf position referred to are those used by AIMS (Baker *et al* 1991, Moran *et al* 1991). A summary of conditions on "no outbreak" reefs in each of the different sectors and cross shelf positions on the Great Barrier Reef is outlined in Table 1.

Comparing the decision key with the previous classification system

The decision key was applied to empirical data. The ease of application was considered in terms of the clarity of the questions posed and the possibility of answering the questions unambiguously. The purpose of the key was to define the decision rules which experts at AIMS have used to classify reefs. If the classification achieved by the key matched that arrived at by expert assessment then the key serves its purpose. In all 622 cases, classification by the formalised key matched that achieved by expert opinion. The decision rules had, therefore, been correctly identified and formalised.

Results

The decision key illustrated in Fig. 1 is the result of application of all the information available on reefs of the Great Barrier Reef (GBR) which were manta towed by the AIMS Broadscale Survey team (1985-1990). In distinguishing reefs which are recovering and reefs which have no evidence of an outbreak, using the second last question in the key, the 95% confidence limits in Table 1 should be used. Thus, the condition "Total COTS> No outbreak" asks: Is the present number of crown-of-thorns starfish more than the upper 95% confidence limits of no outbreak levels? In testing the key, the decision criteria were found to be clear and unambiguous.

The use of the key can best be understood by application. For this purpose we provide hypothetical (but realistic) data for five reefs in Table 2. Reefs Alpha and Beta classify quickly to active outbreak and no outbreak status. These reefs are typical of the majority of reefs found on the GBR. Data presented for reefs Gamma, Delta and Epsilon are less typical and far more ambiguous. For reef Gamma, the variance to mean ratio indicates that the starfish were aggregated and the mean number of starfish

per manta tow are borderline indicating a possible classification as "active outbreak". However, by the decision key, the total number of starfish and dead coral cover in the presence of starfish are both less than the threshold. Given that there is no other information on this reef it is classified as "no outbreak". For reef Delta, three of the four criteria required for classifying a reef as supporting an outbreak are marginally satisfied at the second branch of the decision tree thus the reef can be unambiguously labelled as "active outbreak". Reef Epsilon does not have an outbreak but does have previous reliable information (in the form of previous AIMS manta tow data) indicating that an active outbreak did occur here recently. The distinction to be made now is whether the reef is in recovery or whether it no longer has evidence of an outbreak. As there is no standard AIMS manta tow data on this reef prior to outbreak status, data are compared with reefs in the Townsville sector and mid-shelf position (Table 1). This comparison indicates that, although the starfish population seems to be within normal levels, the live and dead coral cover has not yet recovered to normal levels. The live coral cover is normally higher and dead coral cover should be lower. Thus, reef Epsilon is a "recovering" reef.

Discussion

The decision key introduces consistency and transparency to a classification system used by experts at AIMS for labelling reefs with regard to outbreaks of crown-of-thorns starfish on the Great Barrier Reef (GBR). The framework and criteria of the decision tree can be transferred to other parts of the world which support populations of crown-of-thorns starfish. The specific thresholds within criteria used here are applicable only to: (a) the AIMS manta tow sampling technique and (b) the GBR.

With different data sampling techniques a different proportion of the population may be sampled thus demanding different threshold levels for criteria such as "Mean number of crown-of-thorns starfish counted per manta tow on a reef". For example, if the starfish data were collected using SCUBA gear then relatively higher counts of starfish per unit search effort would define an outbreak within this decision key. This is due to the larger proportion of starfish which would be available and counted using this technique (Fernandes 1990, Moran and De'ath 1992a). Keesing and Lucas (1992) mention that feeding rates of crown-of-thorns starfish vary between regions. Consequently, different absolute numbers of starfish might be considered an outbreak in different regions based upon the amount of coral mortality associated with each population. Thus, the thresholds within the criteria used, including coral cover criteria, would need to be generated based on local information.

This key will facilitate exploration of the utility and validity of the, previously undocumented, AIMS classification scheme for outbreaks of crown-of-thorns starfish on the GBR. As suggested by Keesing and Lucas (1992), there may be room for improving the criteria used. Perhaps the thresholds of the criteria should be altered. Moran and De'ath (1992b) suggest that an average density of 0.22 starfish per manta tow might be a more appropriate density of starfish to define an outbreak. They calculate this to equal 1500 starfish counted by SCUBA dives per km^2. This is higher than the 1000 starfish km^{-2} number suggested by Keesing and Lucas (1992) especially considering that Moran and De'ath referred to SCUBA estimates and Keesing and Lucas to absolute numbers. Our suggested average density of starfish counted per manta tow within an outbreak is greater still than that suggested by Moran and De'ath

(1992b)(i.e. 0.5 or 1.0). However, if a smaller population is aggregated with high dead coral cover then the reef would still be classified as supporting an active outbreak by the present classification scheme. Use of coral cover criteria, as we have done, was recommended by Moran and De'ath (1992b) to mitigate potential misclassifications.

By clarifying the working definition used by researchers and managers on the Great Barrier Reef, we hope to stimulate a more critical assessment of the biological meaning of *Acanthaster planci* outbreaks and to facilitate international understanding and comparison of research results.

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Table 1. Summary of the characteristics of reefs on the Great Barrier Reef (1985-1990) which have been classified as having no evidence of an outbreak (NO). This data is used for distinguishing "outbreak" from "recovering" reefs if there is no standard AIMS manta tow data of pre-outbreak conditions available for the reef being keyed out. n = sample size; COTS = numbers of crown-of-thorns starfish; CL = confidence limits; VMR = variance to mean ratio; DCC = dead coral cover category (from 0 to 5); LCC = live coral cover category (from 0 to 5).

Table 2. Example of data used to classify reefs with regard to outbreaks of crown-of-thorns starfish and of the application of the decision key. COTS = numbers of crown-of-thorns starfish; CL = confidence limits; VMR = variance to mean ratio; DCC = dead coral cover category (from 0 to 5); LCC = live coral cover category (from 0 to 5).

Fig. 1. Decision key to classify individual reefs with regard to crown-of-thorns starfish outbreaks on the Great Barrier Reef. The key is based on manta tow survey data as collected by the Australian Institute of Marine Science.

Sector of GBR (as in Baker et al 1991)	Cross shelf position (n)	Mean COTS/ tow	95%CL mean COTS/ tow	Mean total COTS/ reef	95%CL total COTS/ reef	Mean VMR/ reef	95%CL VMR/ reef	Median DCC/ reef (range)	Median LCC/ reef (range)
Cape Grenville	n/a (34)	0.023	0.020	0.706	0.546	0.380	0.271	1 (1-3)	2-3 (1-4)
Princess Charlotte Bay	n/a (36)	0.012	0.011	0.750	0.682	0.220	0.153	1 (0-1)	2 (1-4)
Cooktown/ Lizard Island	Inner (9)	0	0	0	0	0	0	1 (1-2)	2 (1-3)
	Mid (35)	0.013	0.009	0.571	0.464	0.324	0.213	1 (1-2)	2 (1-3)
	Outer (19)	0	0	0	0	0	0	1 (0-1)	2 (1-2)
Cairns	Inner (11)	0	0	0	0	0	0	1 (1)	2 (1-3)
	Mid (15)	0.004	0.006	0.2	0.21	02	0.21	1 (0-1)	2 (1-4)
	Outer (10)	0	0	0	0	0	0	1 (0-1)	2 (1-3)
Innisfail	Inner (13)	0	0	0	0	0	0	1 (0-2)	3 (1-4)
	Mid (2)[1]	0	0	0	0	0	0	0-1	1-2
	Outer (10)	0.001	0.003	0.100	0.196	0.100	0.196	1 (1)	1-2 (1-3)
Townsville	Inner (5)	0	0	0	0	0	0	1 (1)	2 (2)
	Mid (17)	0.139	0.076	8.588	4.649	1.330	0.455	1 (0-2) n=13	2 (2-3) n=13
	Outer (17)	0.010	0.017	0.471	0.715	0.209	0.284	1 (0-1) n=15	2 (2-3) n=15
Cape Upstart	Inner (0)[2]	-	-	-	-	-	-	-	-
	Mid (45)	0.036	0.026	1.800	1.101	0.763	0.485	1 (0-3)	2 (1-3)
	Outer (18)	0.006	0.006	0.222	0.198	0.222	0.198	1 (1-2)	2 (1-4)
Whitsundays	n/a (76)	0.013	0.015	0.474	0.484	0.293	0.286	1 (0-2)	2 (1-4)
Pompey Complex	n/a (65)	0.005	0.005	0.292	0.291	0.134	0.091	1 (0-2)	3 (1-4)
Swains	n/a (100)	0.048	0.023	1.370	0.566	0.614	0.206	1 (0-3)	3 (1-5)
Capricorn Bunker	n/a (30)	0.004	0.006	0.400	0.655	0.111	0.122	1 (0-3)	3 (2-5)

[1] Due to insufficient data for "no outbreak" midshelf reefs in the Innisfail sector, use data of midshelf reefs in the Cairns section for comparison.

[2]Due to insufficient data for "no outbreak" inner shelf reefs in the Cape Upstart sector, use data of inner shelf reefs in the Townsville sector for comparison.

Reef name	Total COTS	Mean COTS	VMR	Median DCC on tows with COTS	Median DCC	Median LCC	Other data	Status
Alpha	330	11.4	17.1	2	2	1	-	Active outbreak
Beta	0	0	n/a	n/a	1	3	-	No outbreak
Gamma	15	0.5	11.2	1	1	2	-	No outbreak
Delta	19	0.7	3.6	2	2	1	-	Active outbreak
Epsilon (midshelf reef, Townsville sector)	5	0.1	0.9	2	2	1	Previous AIMS manta tow data on outbreak (source, date)	Recovering