Final Report on the Results of COTSAC Ecological Research:
December 1985 - June 1989

P.J. Moran, Study Leader & D.B. Johnson, Administrator



Australian Institute of Marine Science

The Crown-of-thorns Study

Crown-of-thorns Study Report 11

February 1990

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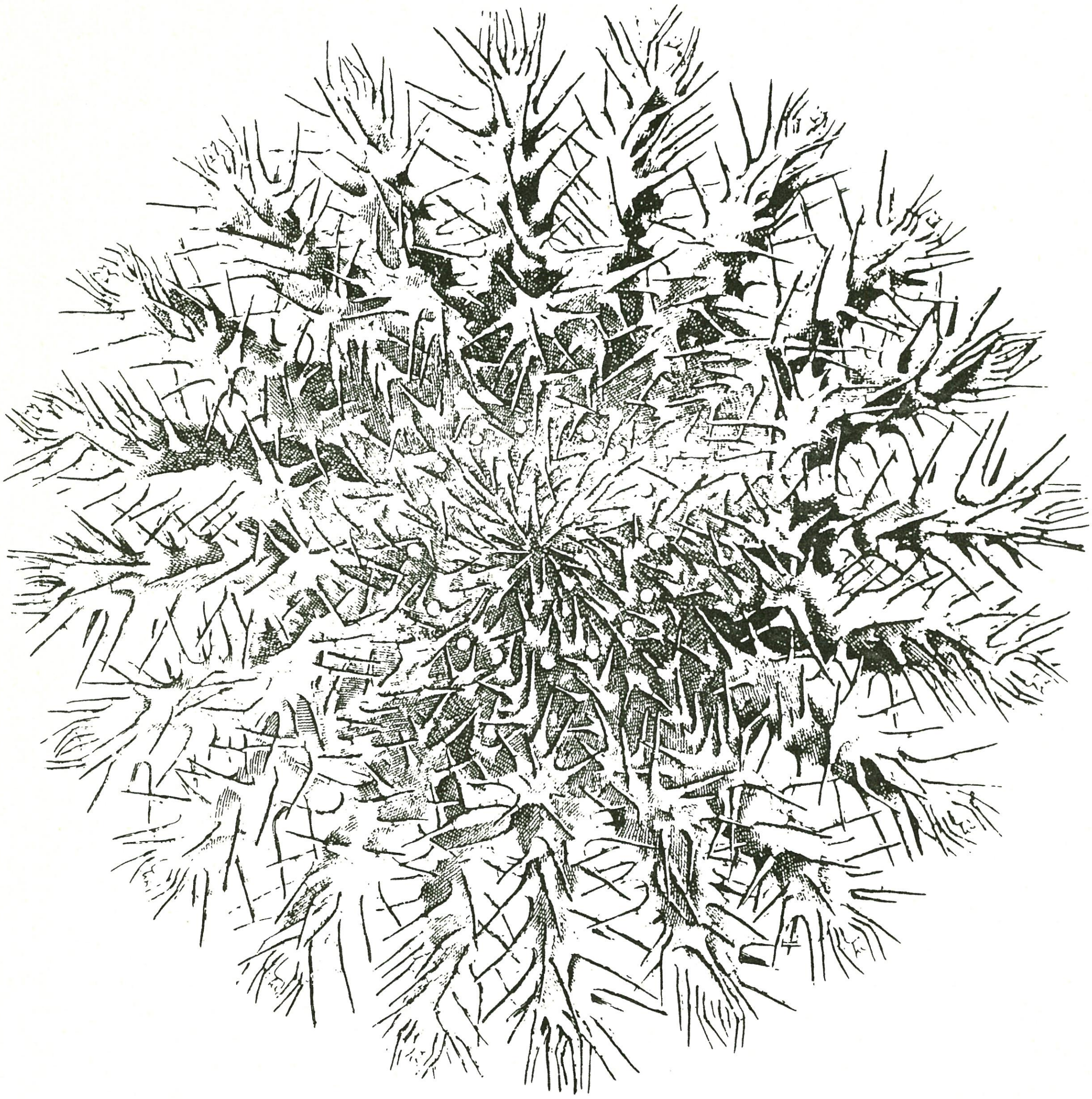

The crown-of-thorns starfish

"And so the theories go,
in dizzying number and diversity."
K. Gouldthorpe (1968).

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## PREFACE

This document provides an overview of the program of ecological research on the crown-of-thorns starfish (*Acanthaster planci*) which was coordinated by the Australian Institute of Marine Science (AIMS) from December 1985 to June 1989. The program was supported using funds allocated by the Great Barrier Reef Marine Park Authority (GBRMPA). As these funds arose from the recommendations of the Crown of Thorns Starfish Advisory Committee to GBRMPA, they have been referred to as COTSAC funds.

The primary objective of this overview is to summarise the results of the ecological projects. These have been drawn from unpublished and internal reports or scientific papers. The quality and quantity of the findings which have emanated from this program serve to highlight the tremendous productivity that was achieved during the course of the program. Such findings have immeasureably advanced understanding of the crown-of-thorns phenomenon across many scientific disciplines. It is well to consider that such gains were made in a relatively short period and at a time when funding was continually uncertain. Given that it is still just less than a year since this phase of the program was completed, many more important findings are expected as data are analysed and written up for publication.

Apart from highlighting the ecological results of the program this document also serves to provide a background to the development of the program and its organisation and administration. In terms of the latter a complete series of budgets have been included which detail how funds were allocated and expended during the course of the program. For more detailed information on individual projects or administration the reader is referred to the 10 technical reports published previously. This document is the final volume in that series.

The authors would like to thank the Director of AIMS, Dr Joe Baker, for his unstinting help and advice throughout the duration of the program and for reviewing earlier drafts of this document. The staff of AIMS also gave their unqualified support to the program. In particular, the authors wish to acknowledge the assistance of all research staff involved in the program who provided, sometimes at quite short notice, reports of

their research. Interpretation of the results of this research in the present document necessarily remains the responsibility of the authors.

**PLEASE NOTE: At the time of writing some of the results in this document had not been published in refereed scientific journals. These results should not be cited without careful reference to the published literature.**

## INTRODUCTION

During 1984 the Great Barrier Reef Marine Park Authority (GBRMPA) established the Crown of Thorns Starfish Advisory Committee (COTSAC) in response to general concerns about the seemingly widespread occurrence of outbreaks of the crown-of-thorns starfish (COTS hereafter), *Acanthaster planci*, on the Great Barrier Reef (GBR). The objectives of the Committee were to review what was known about the starfish at that time, including the results of previous research, and to recommend to GBRMPA the type of research and monitoring that should be undertaken in the future.

At the beginning of 1985 COTSAC recommended that a coordinated research program be undertaken over 4-5 years which would lead to a substantial improvement in understanding of the COTS phenomenon. A total of 12 research areas were identified and it was recommended that funds of approximately $3 million be allocated to support this research effort (COTSAC, 1985).

Towards the end of 1985, and after a further investigation by a Senate Standing Committee on Environment and Conservation (Milton, 1985) the Federal Government allocated $971,000 to GBRMPA for the first year of the research program. In response, a Record of Understanding was established in which it was agreed that the Australian Institute of Marine Science (AIMS) would be responsible for coordinating the "mainly ecological" projects, while GBRMPA would coordinate all management related projects. Subsequently, both institutions advertised jointly seeking expressions of interest and research proposals from throughout Australia. Those that were ecological in nature were reviewed by a Panel (COTSAC Integrated Scientific Research Allocations) convened by AIMS (which included external representation), whilst those that were management related were vetted by a small group of experts appointed by GBRMPA in each field.

The overall research program, including both management-related and ecological projects, was recommended by the Crown of Thorns Starfish Advisory Review Committee (COTSARC) in February 1986. This Committee was established by GBRMPA to review the progress of the program and to advise on the allocation of funds and the future directions for research. It was chaired by Professor J.M. Swan and comprised senior managers and scientists, politicians and representatives from private industry. For administrative reasons a senior scientist could not be appointed to coordinate the program (as recommended by COTSAC) and so the ecological and management related projects were individually coordinated by Dr P. Moran and Dr L. Zann respectively.

Since 1985 the Federal Government has provided additional funds to the program on an annual basis (Zann and Moran, 1988). By 30 June 1989 it had allocated, through GBRMPA, just over $3 million for research on COTS. These funds were used to develop an integrated, multidisciplinary research program comprising 58 separate projects and involving the collaboration of almost 70 senior scientists from throughout Australia and overseas.

The group of ecological projects coordinated by AIMS was termed The Crown-of-thorns Study. Since the Study began AIMS has coordinated 40 different research projects; 11 of these being conducted by investigators at other organisations. During the period from 1 December 1985 to 30 June 1989 AIMS received $1,997,960 million for this research from GBRMPA. In keeping with its own commitment to undertake research on the COTS problem AIMS has provided about the same amount of support to the Study. This has been by way of shiptime, computing facilities, personnel, and administrative and technical support (see below). By 30 June 1989 almost all projects within the Study (apart from on-going or new projects) had been successfully completed.

**References**

**COTSAC (1985).** Report submitted to the Great Barrier Reef Marine Park Authority by the Crown of Thorns Starfish Advisory Committee (Chairman: K.J. Back). Great Barrier Reef Marine Park Authority, Townsville. 49p.

**Milton, P. (1985).** Report of the House of Representatives Standing Committee on Environment and Conservation. Protection of the Great Barrier Reef. Australian Government Publishing Service, Canberra. 39p.

**Zann, L.P. and Moran, P.J. (1988).** A coordinated research program on the *Acanthaster* phenomenon on the Great Barrier Reef. Proceedings of the Sixth International Coral Reef Symposium 2: 177-182.

## LIST OF PROJECTS AND INVESTIGATORS

This section provides a list of all ecological projects supported by COTSAC funds. The following information is provided for each project: project number and title, chief investigator(s), collaborator(s) (NA means Not Applicable), project duration and status (as at 30 June 1989).

Those projects conducted by AIMS essentially were divided into four groups: (1) Population dynamics of the predator, (2) Dynamics of the prey and ecosystem context, (3) Interaction of predator and prey, (4) Technological and analytical methodology. One project, which evaluated the biological effects of a COTS control program, was put into a separate group (group 7). Projects that were conducted outside of AIMS were amalgamated into group 6. The funds used to support the general organisation of the Study were allocated from an administrative project within group 5.

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**Project No.** 1(a).
**Title** Geographic patterns in genetic variation of *Acanthaster planci* populations.
**Investigators** Dr J. Benzie and Dr J. Stoddart.
**Collaborators** NA.
**Duration** July 1986 - December 1988.
**Status** Completed.

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**Project No.** 1(b).
**Title** Inheritance patterns of isoenzymes in *Acanthaster planci*.
**Investigators** Dr J. Stoddart and Dr J. Benzie.
**Collaborators** NA.
**Duration** October 1986 - March 1988.
**Status** Completed, insufficient enzyme activity achieved with larvae although juvenile starfish proved successful.

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| | |
|---|---|
| **Project No.** | 1(c). |
| **Title** | A field test of the larval starvation hypothesis for *Acanthaster planci*. |
| **Investigators** | Dr R. Olson. |
| **Collaborators** | Dr J. Lucas (James Cook University (JCU)). |
| **Duration** | October 1985 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 1(d). |
| **Title** | Tactile stimulation as a primary settlement cue for larvae of *Acanthaster planci*. |
| **Investigators** | Dr R. Olson. |
| **Collaborators** | NA |
| **Duration** | October 1986 - December 1987. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 1(e) |
| **Title** | Substrate selection by larvae of *Acanthaster planci*. |
| **Investigators** | Dr R. Olson. |
| **Collaborators** | Dr J. Lucas (JCU). |
| **Duration** | October 1986 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 1(f) |
| **Title** | Development of techniques for the production of large numbers of larvae and juveniles of *Acanthaster planci*. |
| **Investigators** | Mr P. Dixon. |
| **Collaborators** | Dr R. Olson. |
| **Duration** | October 1985 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 1(g) |
| **Title** | Feeding rate of *Acanthaster planci* in the field. |
| **Investigators** | Dr D. Klumpp, Dr J. Lucas (JCU) and Mr J. Keesing. |
| **Collaborators** | Dr P. Moran. |
| **Duration** | April 1986 - June 1989. |
| **Status** | Completed: additional funds allocated in 1989/90 to support Ph.D student during thesis preparation. |

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|---|---|
| **Project No.** | 1(h) |
| **Title** | Feeding preferences of *Acanthaster planci* in the field. |
| **Investigators** | Dr P. Moran. |
| **Collaborators** | NA. |
| **Duration** | April 1986 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 1(i) |
| **Title** | Rate of decomposition of adult *Acanthaster planci* in the field. |
| **Investigators** | Dr P. Moran. |
| **Collaborators** | NA. |
| **Duration** | October 1986 - December 1987. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 1(j) |
| **Title** | Ephemeral patches of phytoplankton in the central Great Barrier Reef as a potential food source for larvae of *Acanthaster planci*. |
| **Investigators** | Dr M. Furnas and Mr P. Liston. |
| **Collaborators** | NA. |
| **Duration** | May 1986 - June 1989. |
| **Status** | Completed: additional funds allocated in 1989/90 to support Ph.D student during thesis preparation. |

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| | |
|---|---|
| **Project No.** | 1(k) |
| **Title** | Spawning success and fertilisation rates of *Acanthaster planci*. |
| **Investigators** | Dr J. Benzie, Mr P. Dixon and Dr P. Moran. |
| **Collaborators** | Dr K. Black (Victorian Institute of Marine Sciences (VIMS)). |
| **Duration** | June 1988 - June 1989. |
| **Status** | Fieldwork completed, data analysis underway. |

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| | |
|---|---|
| **Project No.** | 1(l) |
| **Title** | The role of bacteria from coralline algae in outbreaks of crown-of-thorns starfish. |
| **Investigators** | Dr C. Johnson and Dr D. Sutton (Sir George Fisher Centre). |
| **Collaborators** | Mr P. Dixon. |
| **Duration** | June 1988 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 2(a) |
| **Title** | Recovery and recolonisation of coral communities. |
| **Investigators** | Dr T. Done and Dr P. Moran. |
| **Collaborators** | NA. |
| **Duration** | December 1985 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 2(b) |
| **Title** | Interpretation of the history of disturbance to coral communities through analysis of morphology and population structure in massive corals. |
| **Investigators** | Dr T. Done. |
| **Collaborators** | Dr P. Sale (University of Sydney). |
| **Duration** | January 1986 - December 1988. |
| **Status** | Completed. Further funds allocated in 1989/90 to extend original objectives of project. |

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| | |
|---|---|
| **Project No.** | 2(c) |
| **Title** | Genetics of population fluctuations of corals. |
| **Investigators** | Dr J. Stoddart. |
| **Collaborators** | NA. |
| **Duration** | May 1986 - March 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 2(d) |
| **Title** | Growth and survivorship of coral remnants following outbreaks of *Acanthaster planci*. |
| **Investigators** | Dr T. Done. |
| **Collaborators** | NA. |
| **Duration** | December 1985 - December 1988. |
| **Status** | Continuing as part of AIMS Core Research. |

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| | |
|---|---|
| **Project No.** | 2(e) |
| **Title** | Effects of outbreaks of *Acanthaster planci* on fish communities. |
| **Investigators** | Dr D. Williams. |
| **Collaborators** | Dr P. Doherty (Griffith University). |
| **Duration** | December 1985 - December 1988. |
| **Status** | Continuing as part of AIMS Core Research. |

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| | |
|---|---|
| **Project No.** | 3(a) |
| **Title** | Macro-scale studies of the distribution and abundance of *Acanthaster planci* and corals on the Great Barrier Reef. |
| **Investigators** | Dr P. Moran and AIMS Crown-of-thorns survey team members. |
| **Collaborators** | NA. |
| **Duration** | January 1986 - June 1989. |
| **Status** | Annual surveys along the GBR continuing. |

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|---|---|
| **Project No.** | 3(b) |
| **Title** | Meso-scale studies of the distribution and abundance of *Acanthaster planci* and corals on selected reefs. |
| **Investigators** | Dr P. Moran. |
| **Collaborators** | NA. |
| **Duration** | December 1985 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 3(c) |
| **Title** | Investigation of sampling biases in manta tow survey with particular reference to crown-of-thorns starfish (*Acanthaster planci*). |
| **Investigators** | Dr L. Marsh and Ms L. Fernandes (JCU). |
| **Collaborators** | Dr P. Moran. |
| **Duration** | January 1988 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 3(d) |
| **Title** | Field and laboratory investigations of the line transect technique for monitoring the effects of the crown-of-thorns starfish. |
| **Investigators** | Dr G. Russ (JCU) and Mr C. Mundy. |
| **Collaborators** | Dr R. Reichelt and Dr P. Moran. |
| **Duration** | April 1988 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 4(a) |
| **Title** | Enhancement of substrate reflectance in Landsat imagery with special attention to reef damage by *Acanthaster planci*. |
| **Investigators** | Dr D. Jupp (Commonwealth Scientific and Industrial Research Organisation (CSIRO)) and Dr R. Reichelt. |
| **Collaborators** | NA. |
| **Duration** | February 1986 - June 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 4(b) |
| **Title** | Evaluating procedures for the verification of Landsat images with reference to the effects of *Acanthaster planci* on reefs. |
| **Investigators** | Dr R. Reichelt and Mr S. Bainbridge. |
| **Collaborators** | Dr D. Kuchler (CSIRO). |
| **Duration** | February 1986 - June 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 4(c) |
| **Title** | Numerical models of the hydrodynamic regime around schematized and actual reefs. |
| **Investigators** | Dr K. Black (VIMS), Dr J. Andrews and Mr S. Gay. |
| **Collaborators** | Dr P. Moran. |
| **Duration** | March 1986 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 4(d) |
| **Title** | Numerical models of the hydrodynamic regime around John Brewer Reef. |
| **Investigators** | Dr J. Andrews, Dr K. Black and Mr S. Gay. |
| **Collaborators** | NA. |
| **Duration** | January 1987 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 4(e) |
| **Title** | Dispersal of *Acanthaster planci* outbreaks over the whole Great Barrier Reef - a simulation study. |
| **Investigators** | Dr R. Reichelt. |
| **Collaborators** | Dr D. Green (Australian National University) and Mr S. Bainbridge. |
| **Duration** | February 1986 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 4(f) |
| **Title** | Analyses and models of existing data. |
| **Investigators** | Dr R. Bradbury, Dr R. Reichelt and Dr P. Moran. |
| **Collaborators** | Prof. P. Antonelli (University of Alberta), Dr M. Dale (CSIRO) and Dr D. Green (ANU). |
| **Duration** | December 1985 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 4(g) |
| **Title** | Tagging of *Acanthaster planci* using micro-injectable transponders. |
| **Investigators** | Dr P. Moran. |
| **Collaborators** | Mr. R. Peden (Deakin University). |
| **Duration** | January 1986 - June 1989. |
| **Status** | Waterproofed system completed, field trials commencing. |

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| | |
|---|---|
| **Project No.** | 6(a) |
| **Title** | Determination of *Acanthaster* reef flat infestation patterns by low level aerial photography. |
| **Investigators** | Assoc/Prof. D. Hopley (JCU). |
| **Collaborators** | Dr P. Catt (JCU). |
| **Duration** | April 1986 - December 1986. |
| **Status** | First phase completed 1985/86: funding continued under management-related program. |

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| | |
|---|---|
| **Project No.** | 6(b) |
| **Title** | The dynamics of physiological parameters of high density crown-of-thorns populations. |
| **Investigators** | Dr J. Lucas, Mr B. Kettle and Mr R. Stump (JCU). |
| **Collaborators** | NA. |
| **Duration** | April 1986 - June 1989. |
| **Status** | Investigations into aging continuing; all other objectives completed. |

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| | |
|---|---|
| **Project No.** | 6(c) |
| **Title** | A study of the temporal and spatial distributions of *Acanthaster* larvae in relation to survival and dispersal. |
| **Investigators** | Dr R. Hartwick (JCU). |
| **Collaborators** | NA. |
| **Duration** | April 1986 - June 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 6(d) |
| **Title** | Simulation of large-scale population dynamics of crown-of-thorns starfish in the Great Barrier Reef system. |
| **Investigators** | Dr M. James, Dr L. Bode, Prof. K. Stark, Mr L. Marsh and Mr I. Dight (JCU). |
| **Collaborators** | NA. |
| **Duration** | April 1986 - March 1988. |
| **Status** | First phase completed: refinement of hydrodynamic model continuing. |

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| | |
|---|---|
| **Project No.** | 6(e) |
| **Title** | An assessment of the *Acanthaster* phenomenon through a consideration of the life history strategy of *A. planci*. |
| **Investigators** | Dr M. James, Mr I. Dight, Prof. R. Jones, Dr L. Bode, and Prof. K. Stark (JCU). |
| **Collaborators** | NA. |
| **Duration** | April 1988 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 6(f) |
| **Title** | Field studies of aspects of the ecology of *Acanthaster planci*. |
| **Investigators** | Assoc/Prof. R. Endean, Dr A. Cameron and Mr L. DeVantier (University of Queensland). |
| **Collaborators** | NA. |
| **Duration** | April 1986 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 6(g) |
| **Title** | Dynamics of recuitment and the densities of juvenile crown-of-thorns starfish between 15°S and 20°S on the Great Barrier Reef. |
| **Investigators** | Dr P. Doherty (Griffith University). |
| **Collaborators** | Mr J. Davidson. |
| **Duration** | April 1986 - June 1989. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 6(h) |
| **Title** | Analysis of physical mechanisms controlling plankton patchiness on the Great Barrier Reef. |
| **Investigators** | Dr J. Parslow and Dr A. Gabric (Griffith University). |
| **Collaborators** | NA. |
| **Duration** | April 1986 - June 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 6(i) |
| **Title** | Development of monoclonal antibodies against larvae of *Acanthaster planci*: a pilot study to detect and characterise larval membrane markers for this species. |
| **Investigators** | Dr P. Hanna, Dr V. Lee and Dr B. Richardson (Deakin University). |
| **Collaborators** | NA. |
| **Duration** | April 1986 - December 1988. |
| **Status** | Completed: further testing and refinement of technique to continue. |

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| | |
|---|---|
| **Project No.** | 6(j) |
| **Title** | Dynamics of the *Acanthaster*/hard coral interaction. |
| **Investigators** | Mr D. Fisk and Dr V. Harriott (Reef Research and Information Services). |
| **Collaborators** | NA. |
| **Duration** | April 1986 - December 1988. |
| **Status** | Completed. |

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| | |
|---|---|
| **Project No.** | 6(k) |
| **Title** | The within-reef distribution pattern of juvenile *Acanthaster planci*. |
| **Investigators** | Prof. H. Choat (JCU). |
| **Collaborators** | Dr P. Moran. |
| **Duration** | November 1987 - February 1988. |
| **Status** | Project terminated after initial field surveys as a suitable population of juvenile crown-of-thorns starfish could not be identified. |

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| | |
|---|---|
| **Project No.** | 7(a) |
| **Title** | Assessment of the biological effects of a crown-of-thorns starfish control program at Grub Reef. |
| **Investigators** | Dr P. Moran and Mr D. Johnson. |
| **Collaborators** | Dr L. Zann and Ms S. Driml (GBRMPA). |
| **Duration** | June 1986 - January 1987. |
| **Status** | Completed. |

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## FINANCE AND ADMINISTRATION

A total of $1,997,960 was allocated to ecological projects by GBRMPA during the period from 1985/86 to 1988/89. Of that amount, $1,532,993 was allocated to internal projects while the remainder ($464,967) was given to support projects conducted at other institutions. The amounts that were allocated annually are shown in Table 1.

A complete summary of the expenditure incurred during each year of the Study is presented in Table 2. These figures contrast with the projected allocations given in previous reports. Such variations result from unforeseen expenditure, savings or income. The last of these, which was derived from several projects (see below) enabled a greater amount of funds to be expended than was actually allocated.

Examination of Table 2 indicates that approximately 58% of funds were expended on salaries and allowances (i.e. for diving and travel). During the course of the Study a total of 16 full time staff (average of 10 staff per year) were employed at AIMS to undertake ecological research.

Collaborative expenses were the next largest area of expenditure involving just over 17% of funds. This heading included the following major expenses: administrative on-costs (calculated as 15% of gross salaries), research grants to collaborators (e.g. Victorian Institute of Marine Sciences), as well as general costs associated with external collaborators (e.g. on-site accommodation).

Expenditure relating to Stores included the purchase of stationery, diving equipment, field equipment, general research items and the construction of specialist equipment by AIMS workshops. Several major items of capital equipment also were purchased during the course of the Study. These included: a disk drive for AIMS' main computer (RA81-AD: $33,000), 4 National Panasonic portable computers for seagoing and laboratory use (FT70: $14,400), a graphics Laserjet printer (Series 2: $4,450), various computer accessories ($4,200) and software ($2,000), laboratory ($7,382) and field equipment ($8043). Details of this equipment along with those purchased under external projects have been provided to GBRMPA for inclusion on its Assets Register.

Some shiptime was required during 1986/87 and 1987/88 in addition to that supplied by AIMS (Table 3). The funds expended provided an additional 107 days of shiptime to internal projects.

An additional amount of $7,000 was received during the 1988/89 fiscal year. These funds resulted from the sale of equipment constructed for project 1(k) ($1,100) and the reimbursement of funds from project 6(k) ($4,000) and projects 2(e), 6(f) and 6(g) (total of about $1,900).

Incidentals included costs associated with advertising and appointment of new staff, diving operations and medicals, equipment hire, fringe benefits tax, undertaking field research on island research stations, contract labour, licences, manuals and analytical services.

A general measure of the expenditure incurred by each project during the period from 1985/86 to 1988/89 can be obtained by consulting the proposed annual allocations to projects outlined in Appendix 1.

**Table 1.** Annual allocation of COTSAC funds to internal (i.e. conducted by AIMS) and external (i.e. conducted by other organisations) projects during the period 1985/86 to 1988/89. Apart from those for the 1985/86 period all allocations were recommended by COTSARC.

| Project | Funds allocated ($) | | | | |
|---|---|---|---|---|---|
| | 1985/86 | 1986/87 | 1987/88 | 1988/89 | Total |
| Internal | 395,076 | 403,640 | 427,277 | 307,000 | 1,532,993 |
| External | 162,924 | 126,860* | 126,183 | 49,000 | 464,967 |
| **TOTAL** | **558,000** | **530,500** | **553,460** | **356,000** | **1,997,960** |

***NOTE:**

Funds for project 6(k) ($10,000) were not expended until 1987/88. The project was unsuccessful and unspent funds ($4,000) were returned.

**Table 2.** Annual expenditure (by major headings) of COTSAC funds during the period 1985/86 to 1988/89 as recorded at the 30th June in each fiscal year. All figures rounded to the nearest dollar.

| Heading | Expenditure ($) | | | | |
|---|---|---|---|---|---|
| | 1985/86 | 1986/87 | 1987/88 | 1988/89 | Total |
| Salaries/ allowances | 96,679 | 302,718 | 271,746 | 222,662 | 893,805 |
| Travel/ subsistence | 19,917 | 16,263 | 22,831 | 10,843 | 69,854 |
| Incidentals | 3,310 | 10,603 | 12,215 | 7,895 | 34,023 |
| Computer equipment | - | 262 | 1,709 | 879 | 2,850 |
| Stores | 83,811 | 36,019 | 13,404 | 15,312 | 148,546 |
| Publishing | - | - | 533 | 4,676 | 5,209 |
| Collab. expenses | 39,920 | 87,727 | 67,722 | 70,499 | 265,868 |
| Vehicles | 16,396 | 4,268 | 17,645 | 8,294 | 46,603 |
| Freight | 448 | 2,528 | 611 | 1,961 | 5,548 |
| Vessel hire | - | 38,155 | 26,709 | - | 64,864 |
| AIMS TOTAL | 260,481 | 498,543 | 435,125 | 343,021 | 1,537,170 |
| External projects | 162,924 | 116,860 | 139,291 | 42,000 | 461,075 |
| TOTAL EXP. | 423,405 | 615,403 | 574,416 | 385,021 | 1,998,245 |

**EXPLANATION OF FIGURES**

Carry forward of: $134,595 into 1986/87; $49,692 into 1987/88; $28,736 into 1988/89; $6,715 into 1989/90.

Total of $4,000 received during 1988/89 from project 6(k).
Total of $3,000 received during 1988/89 from sale of equipment constructed for project 1(k), and reimbursement of funds from projects 2(e), 6(f) and 6(g).

## SUPPORT GIVEN BY AIMS

As stated previously AIMS has provided a great deal of support to internal projects (i.e. those conducted by AIMS staff) funded under COTSAC recommendations. The total notional support given during the period 1985/86 to 1988/89 is estimated at approximately $ 1,816,902. The majority of this was provided by way of salaries, shiptime and computing. A total of 9 Research Scientists and 6 Experimental Scientists from AIMS were involved in undertaking ecological research on COTS from 1985/86 to 1988/89 (approximate notional cost of $426,329). Of these, only Dr P. Moran, was involved in the research on a full-time basis. All 3 of AIMS' vessels (i.e. RV Lady Basten, RV Harry Messel and the RV Sirius) were used to conduct field research at an approximate cost of $1,052,225. In all, about $329,400 of computing time (mainly to projects 2(b), 4(d)(e)(f)) was provided by AIMS at an average cost of $300 per CPU hour. It also provided support to projects through the purchase of capital equipment and stores. The extent of the notional support given to the various ecological projects is shown in Table 1.

Whilst not listed in Table 1, AIMS also provided facilities (i.e. laboratory and office space, transportation, analytical services, library and computing services, workshop services and diving stores and equipment) for a number of external projects, particularly 6(b), 6(c), 6(f), 6(g) and 6(j).

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**Table 3.** Notional support given by AIMS to internal ecological projects during the period 1985/86 to 1988/89. The figures are based on projected usage of facilities as supplied by each chief investigator.

| Project No. | Notional support ($) 1985/86 | 1986/87 | 1987/88 | 1988/89 | Total |
|---|---|---|---|---|---|
| 1(a) | 1,586 | 3,920 | 2,220 | - | 7,726 |
| (b) | 714 | 2,120 | 2,220 | - | 5,054 |
| (c) | 26,000 | - | - | - | 26,000 |
| (d) | - | - | - | - | - |
| (e) | - | - | - | - | - |
| (f) | - | - | - | - | - |
| (g) | 6,534 | 5,800 | 13,740 | 12,916 | 38,990 |
| (h) | 5,568 | 44,700 | 30,780 | 4,080 | 85,128 |
| (i) | 4,267 | 4,000 | 4,380 | - | 12,647 |
| (j) | 72,069 | 21,705 | 69,400 | 45,300 | 208,474 |
| (k) | - | - | - | 43,200 | 43,200 |
| (l) | - | - | - | 124,864 | 124,864 |
| 2(a) | 5,279 | 36,900 | 16,220 | 12,320 | 70,719 |
| (b) | 7,695 | 30,050 | 39,500 | 32,500 | 109,745 |
| (c) | 4,856 | 7,300 | 24,300 | - | 36,456 |
| (d) | 6,545 | 14,100 | 24,200 | 6,200 | 51,045 |
| (e) | 42,970 | 69,700 | 61,150 | 61,150 | 234,970 |
| 3(a) | 8,323 | 9,000 | 49,920 | 70,200 | 137,443 |
| (b) | 5,568 | 19,500 | 14,100 | 7,980 | 47,148 |
| (c) | - | - | - | 14,240 | 14,240 |
| (d) | - | - | - | 9,900 | 9,900 |
| 4(a) | 1,534 | 940 | 1,000 | - | 3,474 |
| (b) | 5,767 | 21,800 | 3,300 | 3,300 | 34,167 |
| (c) | - | - | - | - | - |
| (d) | 13,450 | 143,400 | 102,500 | 34,250 | 293,600 |
| (e) | 1,534 | 6,900 | 24,300 | 13,800 | 46,534 |
| (f) | 36,854 | 52,100 | 47,040 | 26,040 | 162,034 |
| (g) | 1,534 | 3,200 | 4,080 | 4,080 | 12,894 |
| 7(a) | - | - | - | - | - |
| **TOTAL** | **258,647** | **497,135** | **534,350** | **526,320** | **1,816,452** |

## SUMMARY OF ECOLOGICAL RESULTS

A summary of the main results of ecological projects undertaken at AIMS and external organisations is given below. Since it is only a relatively short time since most of the projects were completed many more important findings are expected to come to light during the next few years.

In order to highlight the gains in understanding that have come from this program, the results are given in point-form and grouped together under subject headings rather than by project. There is no doubt that they provide a sound basis upon which future research and management of the COTS phenomenon can be built.

These findings should not be cited without careful reference to the publications listed at the end of this document.

### 1. Population genetics of COTS

**(a)** Patterns of gene flow amongst outbreaking and low density COTS populations in the central and southern sections of the GBR are consistent with the hypothesis of primary outbreaks in the north giving rise to secondary outbreaks further south. While the results indicate that larval dispersal has been dominated by this pattern the notion that additional primary outbreaks also may have occurred in the region cannot be excluded.

**(b)** COTS populations from throughout Australia (i.e. GBR, Dampier Archipelago and Lord Howe Island) show little genetic differentiation from each other, except for those from Lord Howe Island.

**(c)** The data indicate considerable genetic differences between COTS populations in the northern Indian Ocean (e.g. Maldives) and those in the Pacific.

### 2. Reproduction of COTS

**(a)** Field measurements immediately adjacent to starfish that were induced to spawn (using 1-methyladenine) yielded egg and sperm densities of up to 12,000 per l and 400,000 per ml, respectively.

**(b)** Laboratory experiments indicated that fertilisation rates were affected by gamete age, since (at the highest concentrations observed in the field) they declined once eggs or sperm had aged for 6-7 hours or 2-3 hours respectively.

**(c)** Dilution further enhanced this ageing effect for sperm. No fertilisation of eggs occurred at sperm concentrations of less than 10 sperm per ml.

**(d)** Much lower fertilisation rates were obtained using adults collected at the end of the breeding season (i.e. mid January), as opposed to the rates obtained using adults collected during the peak of the spawning season (i.e. early December).

**(e)** Fertilisation rates varied significantly between individuals of the same sex, irrespective of the stage of the breeding season.

**(f)** Synchronous spawning of about 100 male and female starfish (over an area of about 2,000m$^2$) was observed at Wheeler Reef on 5 January 1987. Horizontal plankton trawls undertaken at regular intervals across the southward moving larval patch (whose position was inferred using surface drogues) yielded a total of 72 larvae. While the larvae resembled those of *A planci*, it is possible that they were the progeny of other species.

**3. Larval nutrition**

**(a)** Larval development on the GBR does not appear to be food limited as development time within *in situ* culture chambers was not controlled by food availability. Thus, larval starvation is probably not important in explaining variations in the recruitment of COTS.

**(b)** The larvae of COTS appear to feed selectively on certain species of phytoplankton. Examination of the stomachs of over 75 larvae revealed a wide variety of diatoms and dinoflagellates (over 30 species have been identified to date), dominated by several species (e.g. *Nitzschia closterium* and *Neosynedra tortusa*). Feeding experiments conducted continously over a 24 hr period indicated that the preference of larvae for particular species of phytoplankton changed with the time of day.

**(c)** There was no evidence of bacteria in the stomach contents of larvae indicating that they are not a likely source of food.

**(d)** The feeding intensity of larvae did not vary significantly with the time of day.

**(e)** Detailed surveys of the distribution of potential food for the larvae of COTS indicated that phytoplankton concentrations (determined as chlorophyll) declined across the continental shelf (from the coast to the Coral Sea) and increased down the GBR (from the Cairns zone to the Capricorn Bunker zone).

**(f)** Larvae are not highly sensitive to starvation early in their development. Those that were starved during their first five days had by 10 days of age caught up in development to those that had not been starved.

**(g)** Morphological variations (e.g. length of the brachiolaria arms) amongst larvae of a particular stage are determined principally by the conditions (e.g. availability of food) in which they are raised.

**4. Larval settlement**

**(a)** Larvae probably settle in as short as 10 days and within a maximum of 25 days.

**(b)** Larvae showed settlement in response to a light gradient, settling mostly at an intermediate level of less than $100uE/m^2/s$.

**(c)** Settlement of larvae (within *in situ* culture chambers) is not induced by tactile stimulation.

**(d)** Larvae appear to settle preferentially on certain types of coralline algae, particularly *Lithothamnium pseudosorum*.

**(e)** Settlement of larvae was not uniform over the entire surface of *Lithothamnium pseudosorum*. Some parts induced significant numbers of larvae to settle while others did not. This ability or lack thereof was consistent through time, since repeated experiments using the same parts, but different larvae, generally demonstrated the same result. That is, parts that were poor inducers always were poor and *vice versa*.

**(f)** The ability of some coralline algae to promote settlement of larvae was lost when they were treated with a mixture of antibiotics. This result suggests that bacteria play an important role in cueing the settlement of larvae. Unfortunately, the bacteria responsible could not be isolated.

**5. Hydrodynamics, larval dispersal and recruitment**

**(a)** Eggs and larvae of COTS are approximately neutrally buoyant (their specific gravity varying between 1.02 and 1.03), although they probably become somewhat negatively buoyant just before settlement. Field observations of spawning support these findings.

**(b)** A numerical model of large-scale hydrodynamic processes within the central section of the GBR revealed several important results relating to the larval dispersal of COTS.

- Firstly, that larvae are transported southwards along the continental shelf during summer. The distances over which larvae were predicted to move are consistent with previous hypotheses concerning the southward spread of outbreaking populations.

- Secondly, that there is a general movement of larvae across the continental shelf, from reefs on the outer-shelf to those which border the GBR lagoon. This finding supports previous field observations which indicated that reefs along the lagoon had larger populations of adult starfish.

- Finally, that there are groups of reefs which appear to be situated in areas that are favourable for receiving larvae from upstream reefs. These "sink" reefs were found to have strong connectivity with reefs to the north which were identified as good "sources" of larvae. Such a relationship may well explain why certain reefs are more susceptible to outbreaks of COTS than others.

**(c)** Numerical models of small-scale hydrodynamic processes within the GBR have demonstrated the potential for self-seeding of individual reefs by the larvae of COTS and those of other species with a similar planktonic life history. Several important results have come from these models.

- Firstly, that neutrally buoyant, passive particles may remain on or in the vicinity of individual reefs for up to several weeks, which is comparable to the larval period of many coral reef organisms (e.g. many corals, fishes, echinoderms and gastropods).

- Secondly, some areas within individual reefs retain greater numbers of particles than others as a result of the interaction of certain physical parameters (i.e. wind, tidal and gradient driven currents) with reef morphology (e.g. shape, size and orientation). These areas of high residence often occur along the north-east or south-west corner of each reef.

- Thirdly, longer residence times will be experienced by particles which remain close to the sea bed rather than those which reside near the surface.

**(d)** Good correlation was found between areas of high residence and the locations where outbreaks of COTS were first observed on reefs. This result indicates that hydrodynamics probably have a major influence not only on the dispersal of larvae of COTS but also the location of their initial recruitment.

**(e)** A numerical model of the currents around John Brewer Reef indicated that neutrally buoyant larvae (such as those of COTS) remained within 10km of the reef, 25 days after spawning, despite the presence of low-frequency current speeds of 20 cm/sec. This resulted in high temporal and spatial variability in settlement of these larvae.

**(f)** A numerical model of the relative dispersal of a 1.6 km square patch of tracer through a simulated matrix of reefs, subject to tidal and long-shelf advection, has several implications for the dispersal of COTS larvae.

- If a hypothetical population of ten thousand females produced approximately 10 billion larvae (assuming one million fertilised eggs per female), then the concentration of larvae in the initial patch would be 4000 per $m^2$.

- The model predicts that the patch would be spread over 1000 $km^2$ after 15 days. It would comprise a central region of 25 $km^2$, with larval concentrations of 40 per $m^2$, and a area of 540 $km^2$ containing greater than 4 larvae per $m^2$.

- Whilst the patch did not break up, the concentration of larvae within it was predicted to fluctuate (over scales of a few kilometres) such that small reefs of 2km or less in diameter may experience only low recruitment while settlement within large reefs may vary markedly.

**(g)** Annual monitoring of the distribution and abundance of juvenile starfish from 1985 to 1987 on 16 reefs indicated a pattern that was consistent with the hypothesis of southward dispersal of larvae up to 100-200 km from the parent population. During that period the 1985 cohort was found to be the dominant year class suggesting that large populations of adult starfish can result from enhanced levels of recruitment.

## 6. Starfish dynamics in the field

**(a)** Juvenile COTS are able to survive for at least two weeks without any particulate source of food.

**(b)** Large starfish (>40 cm) rarely hide within the coral reef framework and generally feed during the day. On the other hand smaller starfish (<20 cm) often hide in crevices and underneath corals and feed mainly during the night. The behaviour of moderate-sized individuals (i.e. between 20 and 40 cm in diameter) is intermediate between these two extremes.

**(c)** Generally, COTS are most mobile around dawn or dusk. Their rate of movement depends on their size and the amount of food available. For example, in the case of the latter, rates of movement varied from about 1 m per day in areas of high live coral cover to 10 m per day in extensive areas of low live coral cover.

**(d)** The feeding rate of COTS varied according to the size of the individual. It also was found to be twice as high in summer (maximum just prior to spawning) as in winter. Starfish at Davies Reef consumed about 300 $cm^2$ of coral cover per day.

**(e)** The time taken for individuals to feed ranged from 0.5-11 hours. This depended on the size and type of coral being fed upon.

**(f)** Almost all starfish measured in the field were feeding on hard corals. Some individuals were observed feeding on soft corals and other organisms (e.g. algae, sponges and encrusting invertebrates), although this occurred towards the end of outbreaks when live coral cover was extremely low.

**(g)** Starfish most prefer to feed on corals of the genus *Acropora*, particularly those that are branching or tabulate in form. Least preferred coral genera such as, *Porites* and *Galaxea* generally were eaten when the cover of live coral was low.

**(h)** On the basis of field and laboratory data on feeding it is predicted that a population of about 1,000 individuals per $km^2$ would cause minimal damage to coral communities within individual coral reefs.

**(i)** Approximately 25% of all starfish measured in the field had missing or regenerating arms. This figure varied greatly between different areas.

**(j)** Decomposition of adult starfish in the field takes about 4-6 days.

**7. Mathematical models of starfish dynamics**

**(a)** Cellular automaton models investigating the spatial pattern of starfish abundance showed that aggregations of COTS may be caused by the non-uniform distribution of coral cover on reefs.

**(b)** Investigations of the dynamics of the starfish/coral interaction using simple lumped parameter models produced several findings.

- Firstly, that a number of the hypotheses put forward to account for the occurrence of outbreaks of COTS are plausible. Outbreaks of COTS could occur very rapidly as a result of the processes invoked under the "runoff" and "predation of larvae" hypotheses. A somewhat slower buildup of starfish (over several years) may occur under other hypotheses.

- Secondly, there is no reason to expect that a single process or trigger may be responsible for the occurrence of outbreaks on the GBR.

- Thirdly, that major fluctuations in adult densities can be caused by processes that affect larval mortality.

- Finally, that outbreaks of COTS can arise from small changes in the mortality of adult and juvenile starfish. Thus, outbreaks may occur quite rapidly once predation on low densities of COTS is relaxed.

**(c)** Analysis of the historical data on the distribution and abundance of COTS confirms that there have been 2 series of southward moving outbreaks in the central section of the GBR since the 1960s.

**(d)** The southward movement of outbreaks has been reproduced mathematically using a predator-prey model of the starfish/coral system that takes into account transportation processes.

**8. Broad distribution and effects of outbreaks**

**(a)** Broad-scale surveys of COTS and their effects on corals have been undertaken on 291 reefs throughout the entire range of the Great Barrier Reef during the period 1985/86 to 1988/89. The main results of these surveys are as follows.

- About a third of all reefs surveyed have been affected by outbreaks of COTS over the last 9 years. The main effects are concentrated in the region between Lizard Island and reefs off Bowen. Approximately 52% of reefs surveyed within this region have experienced an outbreak since 1980.

- The number of outbreaking reefs in the Townsville region has declined greatly in the last few years. The majority of these reefs are in the early stages of recovery.

- Outbreaks of COTS are now concentrated in the region of reefs between Ayr and Bowen. The number of outbreaking reefs in this region has increased significantly during the last 2 years.

- Small, outbreaking populations of COTS continue to be recorded on a number of reefs at the far southern end of the Great Barrier Reef.

- About 37% of reefs which had an outbreak of COTS at the time of survey had experienced moderate to high coral destruction over at least a third of their perimeters. A further 13% of reefs were severely affected by the activities of the starfish.

- Overall, the data indicate that the wave of outbreaks is continuing to move further south each year.

**(b)** Within individual reefs outbreaks may appear and disappear very quickly. Major changes in the population abundance of COTS on John Brewer Reef occurred over only a 6 month period. Low to moderate numbers of starfish however, remained on the reef for a further 3 years.

**(c)** Changes in the distribution and abundance of COTS around Green Island followed the same general pattern during outbreaks recorded in the early 1960s and late 1970s.

**9. Effects of outbreaks on corals**

**(a)** Outbreaks of COTS have caused high levels of mortality and injury in corals on the Great Barrier Reef. Surveys of permanent sites before and after recent outbreaks have indicated that coral cover may decline dramatically from an average of 50% to less than 2% within a period of 6 months.

**(b)** Re-establishment of the original cover of corals on mid-shelf reefs off Townsville (e.g. John Brewer and Wheeler Reefs) after outbreaks of COTS has taken 12-15 years.

**(c)** High densities of small, remnant corals (1-10 cm in diameter) may survive large outbreaks of COTS. However, 4 years after the outbreak remnants had contributed little to coral recovery in 3 small study areas on John Brewer Reef.

**(d)** From surveys conducted between 1985 and 1986, it was estimated that a quarter of the massive *Porites* colonies on 5 reefs had been killed completely.

(e) Population models which were used to evaluate the long term implications of this damage produced several important results.

- Firstly, minimum recovery times in excess of 50 years for most of the populations, and 9-100 years for populations in certain areas, assuming no further disturbance.

- Secondly, for *Porites* populations subjected to repeated disturbance every 10-30 years, the model predicted that all large colonies would soon be lost unless background mortality (i.e. mortality experienced between outbreaks) was low and rates of recruitment were high.

- Thirdly, for one reef, John Brewer, the model predicted that if juvenile and adult survivorship were high, the *Porites* population would remain viable in the face of starfish outbreaks every 15 years (as has occurred in the past).

(f) Comparison of the massive coral assemblages on reefs which had been affected by recent outbreaks of COTS with similar assemblages on reefs that had not be affected by outbreaks also has provided a number of interesting results.

- Firstly, the massive coral communities on affected reefs were very different to those on unaffected reefs, based on the total number of corals, colony size and damage. Reefs affected by starfish outbreaks contained about one third the number of massive corals found on unaffected reefs.

- Secondly, while those on unaffected reefs were either intact or only slightly damaged almost 50% of massive corals on affected reefs had suffered mortality over at least one third of their surface.

- Thirdly, the population size structure of the massive coral, *Diploastrea helipora*, was similar on both types of reefs suggesting that it may be resistant to predation by COTS.

- Finally, recovery of the massive coral assemblages on affected reefs (to population size and age structures similar to those on unaffected reefs) was estimated to range from several decades to in excess of 100 years.

**(g)** The pattern of coral recovery on the reef surrounding Green Island has been similar for both recorded outbreaks. The initial stages of recovery were dominated by species of *Acropora*.

**10. Effects of outbreaks on fish**

**(a)** The effects of COTS outbreaks on reef fish communities are highly selective and have not lead to major changes in community structure.

**(b)** The outbreaks produced a major decline in the abundance of coral-feeding butterflyfishes (due to the loss of their food source) and two species of damselfishes (via habitat selection by larvae and subsequent recruitment failure).

**(c)** It is anticipated that the recovery of the damselfishes may be faster than that for the butterflyfishes. Recovery of the former has already begun in conjunction with the initial recovery of the corals.

**11. Methodologies and techniques**

**(a)** An analytical formula has been developed which is a suitable alternative to the numerical model for small-scale hydrodynamic patterns. It can be used to predict the flushing rates or the proportion of particles that remain on a reef after a given period.

**(b)** Passive integrated transponders have shown potential as a technique for tagging starfish. The transponders remained in captive, unfed COTS for an average of 2 months and for as long as 7 months in undisturbed individuals. A fully waterproofed system has been developed for field trials.

**(c)** A means of marking and recapturing individual COTS also has been developed using oxytetracycline techniques. The use of lipofuscin-like pigments also shows potential as a means of determining the age of individual starfish.

**(d)** A total of four monoclonal antibodies have been developed which are specific to the larvae of COTS. This technique makes it possible to distinguish between COTS larvae and those of other starfish which are very similar in appearance. Furthermore, as one of the antibodies reacts with larvae from Japan and Thailand but not those from Australia, the technique has the potential for discriminating between different stocks.

**(e)** The most efficient design for culturing large numbers of larvae consisted of a glass aquarium (400 litre capacity) fitted with an internal filter screen (which retained larvae but allowed continous water flow), and 6 gas bubblers to aerate the water. This design was found to be capable of producing approximately 500,000 larvae within a 16-20 day period.

**(f)** The application of near infra-red aerial photography has proven useful in identifying areas of coral in shallow water that had been recently killed by COTS. The technique shows potential for monitoring the effects of COTS in reef flat environments.

**(g)** Evaluation of remote images and enhancement of substrate reflectance in such imagery has indicated that the spectral and spatial resolution of Landsat MSS data is unsuited to substrate mapping beyond the level of geomorphological zones. Areas of coral and algae on reefs could not be distinguished using Landsat data. Consequently, Landsat imagery is considered not suitable for monitoring the broad-scale effects of COTS outbreaks along the GBR.

**(h)** Investigations of the biases associated with the manta tow method have yielded the following results.

- The technique is useful for determining broad changes in the distribution and abundance of COTS and corals. Other techniques should be used if detailed estimates of abundance are required.

- Further evaluation of the biases associated with recording live and dead coral cover is necessary.

- Underwater visibility should be measured where possible every 10 tows and recording should not be undertaken where visibility is less than 6m.

- Standardisation of several procedures will lead to further refinement of the technique (e.g. reducing the width of search to about 9 m, training new observers and routinely checking experienced observers).

(i) Recent investigations of the line transect method have yielded a number of important results.

- The technique is highly repeatable. That is, repeated measurements of a sample by different observers or the same observer produce similar results.

- Restructuring of some of the benthic lifeform categories relating to algae and submassive coral morphologies is necessary to overcome observer-related biases in the data.

- A transect length of 20m is appropriate for investigating the majority of species or lifeforms at a site.

- A minimum of 6 random transects is required to obtain reliable estimates of the percentage cover of most benthic organisms at a site.

## LIST OF PUBLICATIONS

To date, the following publications have arisen, either directly or indirectly, from ecological research supported by COTSAC funds. Multiple publications for each author are listed in chronological order.

**Antonelli, P. *et al.* (1988).** Nonlinear prediction of crown-of-thorns outbreaks on the Great Barrier Reef. Stochastic Analysis and Applications 6: 349-363.

**Antonelli, P.L. *et al.* (1989).** A diffusion-reaction-transport model for very large-scale waves in crown-of-thorns starfish outbreaks on the Great Barrier Reef. IMA Journal of Mathematics Applied in Medicine and Biology 6:81-89.

**Antonelli, P.L. *et al.* (In press).** Multiple time-scale diffusion modes of starfish and coral state changes over the whole Great Barrier Reef. Journal of Inferential and Deductive Biology.

**Bainbridge, S.J. and Reichelt, R.E. (1988).** Assessment of ground truth methods for coral reef remote sensing data. Proceedings of the Sixth International Coral Reef Symposium 2: 439-444.

**Baker, J. and Moran, P.J. (1987).** A summary of research on ecological aspects of the crown-of-thorns starfish funded by COTSAC and co-ordinated by the Australian Institute of Marine Science. The Crown-of-thorns Study Report No. 3. Australian Institute of Marine Science: Townsville. April 1986, 15 pp.

**Bass, D.K. *et al.* (1988).** Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef: 1986 to 1987. The Crown-of-thorns Study. Australian Institute of Marine Science: Townsville. 145pp.

**Bass, D.K. *et al.* (1989).** Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef: 1987 to 1988. The Crown-of-thorns Study. Australian Institute of Marine Science: Townsville. 172pp.

**Bass, D.K. *et al.* (1989).** Broadscale surveys of crown-of-thorns starfish on the Great Barrier Reef: 1988 to 1989. The Crown-of-thorns Study. Australian Institute of Marine Science: Townsville. 166pp.

**Benzie, J.A.H. and Stoddart, J.A. (1988).** Genetic approaches to ecological problems: crown-of-thorns starfish outbreaks. Proceedings of the Sixth International Coral Reef Symposium 2: 119-124.

**Black, K.P. and Gay, S.L. (1987).** Eddy formation in unsteady flows. Journal of Geophysical Research 92(C9): 9514-9522.

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**Black, K.P. (1988).** The relationship of reef hydrodynamics to variations in numbers of planktonic larvae on and around coral reefs. Proceedings of the Sixth International Coral Reef Symposium 2: 125-130.

**Black, K.P. (1989).** Numerical simulation of steady and unsteady meso-scale eddies. Proceedings of the Ninth Australian Conference on Coastal and Ocean Engineering: Adelaide. pp. 204-208.

**Black, K.P. *et al.* (In press).** A method to determine residence times of neutrally-buoyant matter such as larvae, sewage or nutrients on coral reefs. Coral Reefs.

**Bradbury, R.H. and Mundy, C.N. (In press).** Large scale shifts in biomass of the Great Barrier Reef ecosystem. In: Biomass and geography of large marine ecosystems. Sherman, K. and Alexander, L. (eds.). Westview: Boulder.

**Brahimi-Horn, C. *et al.* (1989).** Lipolytic enzymes of the digestive organs of the crown-of-thorns starfish (*Acanthaster planci*): comparison of the stomach and pyloric caeca. Comparative Biochemistry and Physiology 92B: 637-643.

**Dartnall, J. and Moran, P.J. (1986).** The *Acanthaster* phenomenon: subject index. The Crown-of-thorns Study. Australian Institute of Marine Science, Townsville. 13pp.

**Dight, I.J. *et al.* (1988).** Models of larval dispersal within the central Great Barrier Reef. Patterns of connectivity and their implications for species distributions. Proceedings of the Sixth International Coral Reef Symposium 3: 217-224.

**DeVantier, L.M. and Andrews, G.J. (1987).** Report on surveys of the distribution, abundance and impact of *Acanthaster planci* on the fringing reefs of Lord Howe Island and the Solitary Islands, March to April 1987. The Crown-of-thorns Study. Australian Institute of Marine Science, Townsville. 13pp.

**Doherty, P.J. and Davidson, J. (1988).** Monitoring the distribution and abundance of juvenile *Acanthaster planci* in the central Great Barrier Reef. Proceedings of the Sixth International Coral Reef Symposium 2: 131-136.

**Done, T.J. (1986).** The significance of the crown of thorns starfish. Oceanus 29: 58-59.

**Done, T.J. (1987).** Simulation of the effects of *Acanthaster planci* on the population structure of massive corals in the genus *Porites*: evidence of population resilience? Coral Reefs 6: 75-90.

**Done, T.J. (1988).** Simulation of recovery of pre-disturbance size structure in populations of *Porites* spp. damaged by the crown-of-thorns starfish *Acanthaster planci*. Marine Biology 100: 51-61.

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**Endean, R. *et al.* (1988).** *Acanthaster planci* predation on massive corals: the myth of rapid recovery of devastated reefs. Proceedings of the Sixth International Coral Reef Symposium 2: 143-148.

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## APPENDIX 1

Proposed allocation of COTSAC funds to ecological projects during the period 1985/86 to 1988/89. The figures give a rough indication of the amount of funds expended by each project over the period of the Study. Allocations include carry forward of: $134,595 (*), $49,692 (**), and $28,736 (***).

| Project No. | Funds allocated ($) 1985/86 | 1986/87 | 1987/88 | 1988/89 |
|---|---|---|---|---|
| 1(a) | 16,356 | 39,211 | 39,585 | 24,355 |
| (b) | 1,300 | 146 | - | - |
| (c) | 35,238 | 68,344 | 67,030 | 1,000 |
| (d) | - | 1,400 | 500 | - |
| (e) | 5,000 | 500 | 500 | - |
| (f) | 20,500 | 22,265 | 1,000 | 21,700 |
| (g) | 11,000 | 22,611 | 18,652 | 1,648 |
| (h) | 4,250 | 1,242 | 800 | - |
| (i) | - | 100 | - | - |
| (j) | 17,500 | 11,659 | 11,000 | 11,000 |
| (k) | - | - | - | 7,000 |
| (l) | - | - | - | 17,740 |
| 2(a) | 4,706 | 14,450 | 12,000 | - |
| (b) | 2,200 | 1,000 | 1,000 | 1,000 |
| (c) | 4,500 | 1,941 | 300 | - |
| (d) | - | - | - | - |
| (e) | 793 | 2,005 | 900 | 700 |
| 3(a) | 34,172 | 97,770 | 121,400 | 137,586 |
| (b) | - | 1,360 | 400 | - |
| (c) | - | - | - | 316 |
| (d) | - | - | - | 380 |
| 4(a) | 14,844 | - | - | - |
| (b) | 500 | 3,910 | 28,320 | - |
| (c) | 6,000 | 4,000 | 7,500 | - |
| (d) | 11,144 | 29,881 | 26,300 | 1,332 |
| (e) | 500 | 1,500 | 1,438 | 864 |
| (f) | 13,394 | 52,494 | 15,000 | 15,600 |
| (g) | 10,540 | 3,600 | 500 | 2,500 |
| 5(a) | 161,841 | 121,046 | 110,050 | 100,015 |
| 6(a) | 2,000 | - | - | - |
| (b) | 19,352 | 16,000 | 13,000 | 10,500 |
| (c) | 5,000 | - | - | - |
| (d) | 32,697 | 24,360 | 5,183 | - |
| (e) | - | - | 15,000 | 11,000 |
| (f) | 22,000 | 15,500 | 22,000 | - |
| (g) | 49,797 | 44,000 | 38,000 | 6,000 |
| (h) | 4,000 | - | - | - |
| (i) | 16,078 | - | 16,000 | 10,500 |
| (j) | 12,000 | 17,000 | 17,000 | 8,000 |
| (k) | - | 10,000 | - | 3,000 |
| 7(a) | - | 10,300 | - | - |
| **TOTAL** | **558,000** | **639,595*** | **590,358**** | **393,736***** |