Report of the Committee on the Problem of the Crown-of-thorns Starfish

Publication
Authorised by the
House of Representatives
30 March 1971

Report of the Committee appointed by the Commonwealth and Queensland Governments on the Problem of the Crown-of-thorns Starfish *(Acanthaster planci)*

The Right Honourable William McMahon, M.P.,
Prime Minister of Australia,
Parliament House, Canberra, A.C.T. 2600.

The Honourable J. Bjelke-Petersen, M.L.A.,
Premier of Queensland,
Parliament House, Brisbane, Queensland 4000.

Gentlemen,

We present to you the Report of the Committee appointed jointly by the Commonwealth and Queensland Governments to inquire into and report on the problem of the crown-of-thorns starfish (*Acanthaster planci*) on the Great Barrier Reef.

The Committee was formally appointed by letters dated May 20, 1970, from the Prime Minister on behalf of the Commonwealth and Queensland Governments. These letters set out the Committee's terms of reference, which are given on page 5 of this Report.

Briefly, the Committee was asked to review and report on present knowledge of the crown-of-thorns starfish, obtaining such technical and other advice as deemed necessary; to determine whether the starfish constitutes a threat to the Great Barrier Reef, and if so, the extent of such threat; and, if necessary, to determine what control measures and/or further investigations should be undertaken, indicating an order of priority and an estimate of the costs.

It was not possible to consider the starfish as an isolated organism within the ecosystem of the Great Barrier Reef or to consider the Reef itself simply as a geological structure. Indeed, in pursuing its inquiries the Committee found it necessary to probe many facets of the complex ecology of the Reef. As the subject matter of the Report is not closely arranged in order of the terms of reference, the conclusions reached by the Committee concerning the various matters addressed to it, and the Committee's recommendations, are summarized on page 6.

A feature of the inquiry was the willing cooperation received by the Committee from witnesses and those called upon to assist it, often at short notice and at considerable personal inconvenience. To these persons and to the Commonwealth and Queensland reporting staff, the Committee records its gratitude.

The Committee is also appreciative of the fine work performed by Mr. J. C. Taylor and Mr. B. F. McKeon. On these two officers, at different times, fell the burden of arranging the hearings, the inspections, and the visits of overseas experts, and of obtaining reference material. The Committee is also grateful for the positive contributions each made in the analysis and summation of data before the Committee and in the preparation of the Committee's report.

Yours sincerely,

R. J. Walsh (Chairman)
C. L. Harris
J. M. Harvey

CONTENTS

MEMBERS OF THE COMMITTEE

Professor R. J. Walsh, O.B.E., F.R.A.C.P., F.A.A. (*Chairman*), Professor of Human Genetics, University of New South Wales.

Mr. C. L. Harris, F.A.S.A., Chief Advisory Officer (Administration), Department of Primary Industries, Queensland.

Dr. J. M. Harvey, D.Sc., F.R.A.C.I., Director-General, Department of Primary Industries, Queensland.

Associate Professor W. G. H. Maxwell, Ph.D., D.Sc., D.I.C., Associate Professor of Geology, University of Sydney.

Professor J. M. Thomson, D.Sc., Professor of Zoology, University of Queensland.

Mr. D. J. Tranter, M.Sc., Senior Research Scientist, Division of Fisheries and Oceanography, CSIRO, Cronulla, N.S.W.

Joint Secretaries

Mr. B. F. McKeon, B.Agr.Sc., Assistant Secretary (Agricultural and Biological Sciences), CSIRO, Canberra.

Mr. J. C. Taylor, B.Com., Assistant Secretary, Prime Minister's Department, Canberra.

TERMS OF REFERENCE

The terms of reference were:

1. To review present knowledge of the crown-of-thorns starfish.
2. To seek such expert technical or other advice as the Committee deems necessary and for this purpose, if deemed necessary, to arrange for overseas experts to visit Australia for discussions with the Committee.
3. To determine whether the crown-of-thorns starfish constitutes a threat to the Great Barrier Reef and, if so, the extent of such threat and, if considered necessary, to determine:
   (*a*) what practical measures might be implemented immediately and in the future to reduce or limit such threat;
   (*b*) what further investigations are seen to be necessary or desirable taking account of research being carried out or proposed in Australia or overseas.
4. To nominate priorities with respect to matters determined under paragraph 3 and

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

1. The Committee is of the opinion that the crown-of-thorns starfish, *Acanthaster planci*, does not constitute a threat to the Great Barrier Reef as a whole.

2. There is no danger of substantial erosion of the physical structure of the Great Barrier Reef and no threat to the Queensland coastline or ports. The entire living cover, or even a large proportion of the coral cover of the Reef, will not disappear as a result of *A. planci* activity.

3. The starfish has caused extensive damage to coral, but serious damage is limited to some reefs between the latitudes of Cairns and Townsville. It is emphasized that this damage is not uniform through this region.

4. Recolonization and regeneration of coral have occurred on all reefs that have been examined. The rate of recovery and the diversity of species are variable. Of the 39 genera of corals recorded on Green Island before the starfish infestation, 34 could still be found in June 1970. There is no evidence that the new coral is being seriously damaged by juvenile starfish or residual adults.

5. There are wide variations in the population densities of the crown-of-thorns starfish on coral reefs throughout the Indo-Pacific area. It has been impossible to determine whether the high density of *A. planci* in some areas is a unique or a cyclical phenomenon. The evidence is in favour of its being an episodic event which may have occurred previously.

6. Reef-building is a continuous process of growth and destruction of organisms, including coral and algae. Consolidation of the dead material in the reef mass provides the platform necessary for the continuation of this process. In this context, the feeding by the crown-of-thorns starfish on living coral constitutes, in the long term, portion of the destruction by natural forces within the reef-building process.

7. Tourist activity on the Great Barrier Reef has not declined as a result of damage to coral by the starfish.

8. The weights of commercial fish landed in the Cairns–Townsville region have not changed significantly during the past five years.

9. The Committee cannot make any finding on the cause of the population increase in some areas. Of the several theories advanced, two received particular attention. The hypothesis that local collecting of triton shells (*Charonia tritonis*) has reduced predator pressure on the crown-of-thorns starfish has not been substantiated. With regard to the pollution hypothesis, only trace amounts of pesticides and other organic chemicals were found in the tissues of *A. planci* and other organisms collected from

11. Certain reefs, or portions of reefs, have social or commercial importance. In these situations manual destruction of accessible starfish may be feasible.

12. The Committee is of the opinion that knowledge of reef ecology is inadequate to permit a complete assessment of present and future problems concerning the crown-of-thorns starfish and related matters. In view of the unique importance of the Great Barrier Reef there is, therefore, an urgent need for more research. Investigations should include:

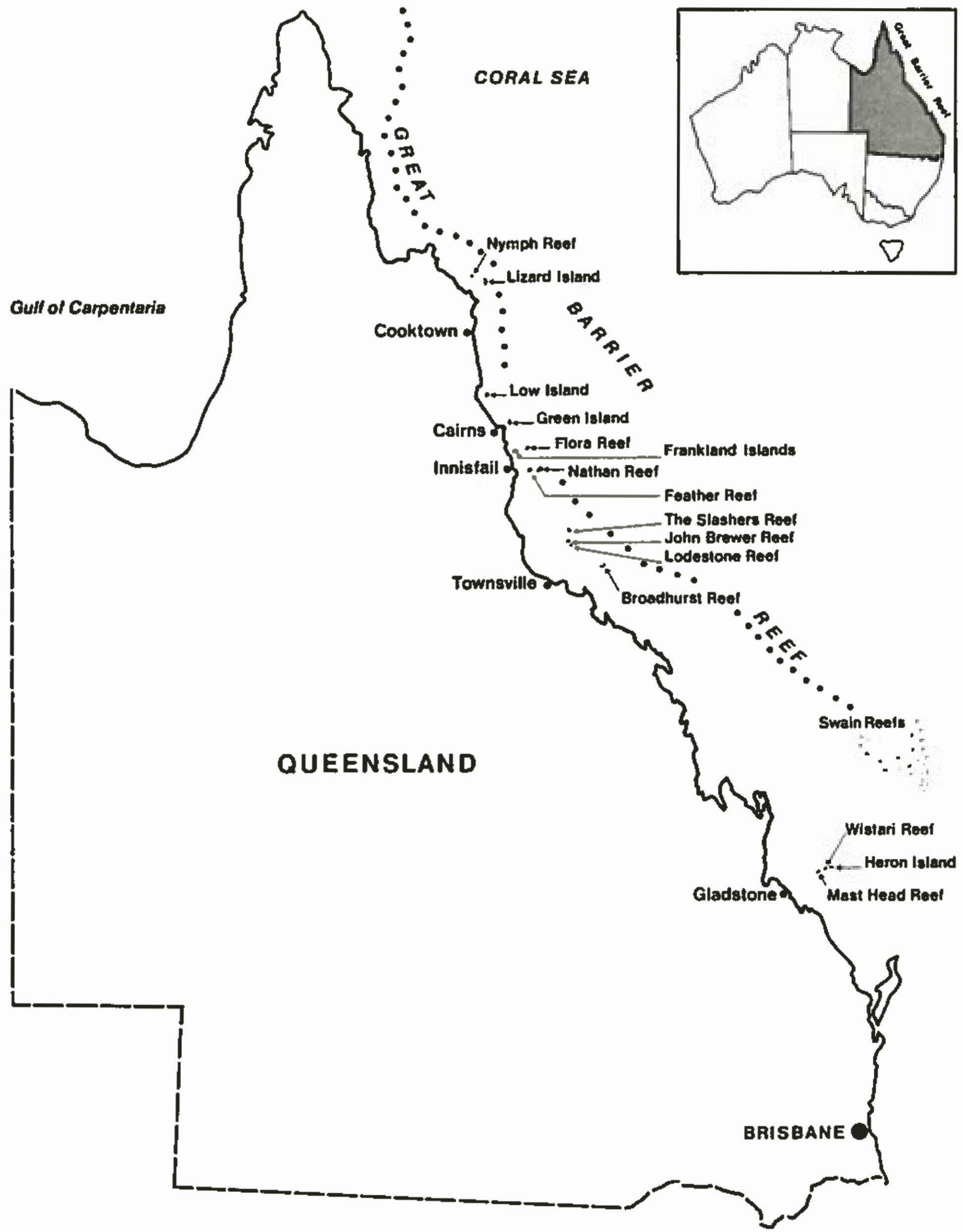
(i) Continued monitoring of *A. planci* population.

(ii) Reef ecology, with particular attention to the biology of *A. planci* and corals.

(iii) Experiments in local control of *A. planci*.

13. It is recommended that a trust fund be established by the Commonwealth and Queensland Governments to provide for research and that an Advisory Committee be appointed to recommend allocations from this fund.

14. It is recommended that a sum of money of the order of $90,000–$120,000 be provided in the first year for the Research Trust Fund and that the sum provided be increased progressively by $20,000 in each of the second and third years.



Map indicating principal reefs of the Great Barrier Reef referred to in this report.

1. INTRODUCTION

Outline of Official Action taken prior to Establishment of the Committee

1.1 To appreciate the situation in relation to the crown-of-thorns starfish (*Acanthaster planci*) on the Great Barrier Reef at the time of the appointment of the Committee, it is desirable to consider briefly developments leading to the establishment of the Committee.

1.2 The first surveys to establish the nature and relative importance of a reported increase in populations of the crown-of-thorns starfish were undertaken by fisheries biologists from the Fisheries Branch of the Queensland Department of Primary Industries in November 1965. These surveys followed advice to the Queensland Government from Dr. J. H. Barnes, of Cairns, reporting increased numbers of the starfish at Green Island and a growing frequency of reports of ciguatera poisoning.* Dr. Barnes suggested the possibility of a previously unsuspected link between fish toxicity and algal growth associated with coral damage caused by the crown-of-thorns starfish. At this time, numbers of the starfish had increased to such an extent that the proprietors of the Green Island resort were employing a diver to remove them by hand from the coral viewing area near the Island.

1.3 A survey embracing reefs in the vicinity of Green Island was undertaken by Mr. N. M. Haysom, State fisheries biologist, and disclosed large populations of the starfish and areas of extensive damage to coral. In his report of December 3, 1965, Mr. Haysom expressed the view that there was no hope of implementing a control programme except in a very localized area, that a better method than hand harvesting was necessary, and that research into the ecology of the starfish was needed.

1.4 In view of the reported situation in the Green Island area, the Queensland Government decided to survey the southern part of the Great Barrier Reef. This survey, carried out by Mr. E. M. Grant, also a State fisheries biologist, covered reefs in the vicinity of Heron Island. No crown-of-thorns starfish were sighted in the survey nor was any damage noted which could be attributed to the starfish.

1.5 On February 1, 1966, the Queensland Government allocated \$20,000 for immediate assistance in controlling the starfish at Green Island and to investigate aspects of the distribution and abundance of the starfish, time of spawning and spawning behaviour, fecundity, growth rate and feeding habits, movement and migration, ecological and other factors influencing its behaviour and occurrence, and possible means of control.

1.6 Arrangements were made for Mr. R. Pearson, a post-graduate marine biology student at the University of Queensland, to be employed full-time on the problem as a State fisheries biologist under secondment to the Department of Zoology of the University. Arrangements were also made for the employment of a technical assistant.

Mr. Pearson. The project was designed as a two-year study and at the end of this period Dr. Endean submitted a report based on his collation and interpretation of the data obtained. The main recommendations in his report were that a programme of hand harvesting of the crown-of-thorns starfish should be implemented and that importation and large-scale breeding of the giant triton shell (*Charonia tritonis*) should be undertaken.

1.8 In memoranda to the Chief Inspector of Fisheries (Queensland), dated July 22 and August 5, 1968, Mr. Pearson advised that he disagreed with several of Dr. Endean's interpretations of the results obtained during the investigation and asked that consideration be given to having population ecologists examine and comment on the report before any decisions based on it were taken. These objections had the effect of questioning the major conclusions drawn in the report from the limited data then available.

1.9 Investigations were continued with the objective of obtaining additional data in respect of the distribution and abundance of the starfish at depths greater than had been examined to that date, and also of examining the extent of coral recolonization. These further investigations did not provide sufficient information to confirm the need for control measures. However, the occurrence of damage down to a depth of 130 ft indicated the difficulty that would be entailed in control and pointed also to the high cost of a control programme.

1.10 Surveys carried out by the Japanese submersible in March 1969 confirmed the occurrence of *A. planci* in deeper waters. An apparent southern limit of the starfish in abundant numbers was located in the vicinity of Broadhurst Reef, off Townsville.

1.11 At this time the Queensland Government referred the matter to the Commonwealth Government and the Prime Minister agreed to a conference of Commonwealth and State officers being convened to review relevant information on the crown-of-thorns situation in relation to the Great Barrier Reef and to consider what action might be taken. Shortly before this conference was held, a request was received from the Westinghouse Survey at Guam for the release of Dr. Endean's report. The Queensland Government acceded to this request and also agreed to the general release of the report. Furthermore, at the request of the Westinghouse Survey, the Chief Inspector of Fisheries visited Guam.

1.12 The controversy which quickly developed reflected the differences of opinion generated by the report in respect of the extent of actual and potential damage to the Great Barrier Reef and of the nature and cause of the apparent increased numbers of starfish.

1.13 At the conference of Commonwealth and State officers held in Brisbane on

(ii) there was a need for further research into the biology, ecology, and population dynamics of the starfish; and

(iii) there was a need for a study of the biology of the giant triton shell (*Charonia tritonis*), a predator of *A. planci*, before any action was taken in relation to multiplication and release of tritons.

1.14 In September 1969, the programme of investigation was placed under the direction of Mr. Haysom, State fisheries biologist, and particular attention was given to the question of recovery of areas damaged by the starfish.

1.15 In November 1969, an *ad hoc* committee was appointed by the Australian Academy of Science to consider the reported widespread destruction of the Great Barrier Reef by the crown-of-thorns starfish. This Committee recommended that:

(i) as it was not considered possible to attempt long-term or widespread control because practical methods were not available, control measures by hand removal, or other methods designed to destroy the starfish *in situ*, should be confined to the vicinity of established tourist areas;

(ii) until further scientific data are available, the ban on collecting the triton shell should be continued and extended to all parts of Australian-controlled waters where it is known to exist;

(iii) research relevant to the problem which is currently in progress should be encouraged and continued; and

(iv) an advisory committee should be set up to determine priorities and to recommend and coordinate research on the biology and physical environment of the Great Barrier Reef.

1.16 Miss J. Henderson, who had been appointed to the Queensland Department of Primary Industries in October 1969, successfully induced spawning of adult starfish in aquaria. Larvae survived up to eighteen days but failed to settle.

1.17 In March 1970, the Queensland Government approved the establishment of field and laboratory facilities at Mourilyan Harbour, near Innisfail, to expand research and survey efforts on the following aspects:

(i) coral regrowth;

(ii) the pattern and rate of destruction of coral;

(iii) starfish growth and behaviour, including migration;

(iv) laboratory studies of growth and predation of starfish;

(v) field observations of spawning.

1.18 Following discussions between the Prime Minister and the Premier of Queensland early in 1970 concerning the mounting publicity being given to the crown-of-thorns

2. PROCEDURE FOLLOWED BY THE COMMITTEE

2.1 The first meeting of the Committee was held in Brisbane on April 17, 1970, to consider the terms of reference and plan the future programme of work. It was agreed that, in view of the technical complexities involved, an invitation would not be extended to the general public to present evidence, but selected experts and bodies having an authoritative interest in and knowledge of the subject matter of the Committee's field of enquiry would be invited to present evidence. A list of persons who accepted the invitation is given in Appendix A.

2.2. The Committee agreed at the initial meeting that the transcript of evidence taken at its sittings would be available to the press and the public,* but in the interests of maintaining an environment conducive to a proper evaluation of scientific evidence, the press and the public would not be admitted during interviews. However, in view of the interest shown in the Committee's activities by the press, radio, and television media, and their reluctance to accept the transcript as an alternative to attendance, the hearings were opened from June 5, 1970.

2.3 The Committee conducted hearings during 1970 at:

Brisbane on May 20–21 and June 4–5;
Sydney on June 13 and 28 and July 2–3;
Townsville on July 17;
Brisbane on July 20–21;
Sydney on August 7;
Brisbane on August 28 and 31.

2.4 With a view to seeing at first hand

(i) areas of reef which had been damaged by the crown-of-thorns starfish,
(ii) areas which were carrying large populations of starfish, and
(iii) areas where no damage from starfish had occurred,

the Committee visited Green Island, Flora, Feather, and Nathan Reefs in category (i), The Slashers, John Brewer, and Lodestone Reefs in category (ii), and Heron, Wistari, and Masthead Reefs in category (iii).

2.5 Three overseas experts were invited to visit Australia for consultation with the Committee. They were:

Professor J. W. Wells, Professor of Geological Science, Cornell University, U.S.A., an authority on corals and coral reefs;
Associate Professor P. M. J. Woodhead, of the Marine Sciences Research Laboratory, Memorial University of Newfoundland, Canada, formerly Director of the Heron Island Research Station;
Dr. R. H. Chesher, Manager of the Florida Marine Ecology Office, Westinghouse Electric Corporation, U.S.A. Dr. Chesher was Chief Scientist for the Westing-

2.6 All three availed themselves of opportunities to visit the Great Barrier Reef. Professor Wells accompanied the Committee on its visit to Heron Island and reefs in the vicinity. Professor Woodhead visited reefs in the Heron Island and Green Island areas at the request of the Committee to conduct surveys of coral growth rate, regeneration, and recolonization. Professor Woodhead's reports are contained in Appendices D and E. Dr. Chesher visited John Brewer and Lodestone Reefs, off Townsville.

2.7 The Committee obtained copies of all authoritative published material to which references could be obtained and which was considered to have a bearing on the subject matter of its enquiry. This material is listed in Appendix C. The Committee was also afforded access to all Government files and documents pertinent to its enquiry.

2.8 While looking primarily to authoritative published technical data as the basis for its review of present knowledge of the crown-of-thorns starfish, the Committee nevertheless made a point of studying the many articles appearing in the press and in semi-technical journals. This study was not particularly productive, the most noticeable feature being the repetitive presentation of eye-catching speculations or exaggerations of the limited facts available.

3. GENERAL BACKGROUND EVIDENCE

Life History, Reproduction, and Behaviour of *Acanthaster planci*

3.1 *Acanthaster planci* is a multi-armed starfish which reaches a size of 60 cm (24 in.) diameter. It is found in association with coral reefs in tropical waters in the Indian and Pacific Oceans. A wide range of pigmentation pattern exists, but there is at present no evidence of subspeciation or of dietary effects.

3.2 Reproduction is achieved by external fertilization following spawning of the reproductive cells into the water. Pearson and Endean (1969) have reported that a female releases between 12 and 24 million eggs during the breeding season which is believed to extend from mid December to mid January. Subsequent recruitment of the young into the adult population depends upon a number of factors—the success of spawning, fertilization, larval development, larval dispersal, larval survival, larval settlement,* and metamorphosis. Each of these may be influenced by the physico-chemical environment and each stage is subject to predation. Optimum conditions for all stages would result in a heavy population recruitment.

3.3 Larvae of *A. planci* have been kept alive for 18 days under laboratory conditions, but had not metamorphosed at the time of death. Based on a breeding season extending from mid December to mid January, the larval life is probably less than a month, as small metamorphosed *A. planci* were found on Fitzroy Reef in mid January 1968. There is very little information on the life cycle and no information on spawning behaviour or fertilization patterns. There is evidence that the metamorphosed starfish

3.4 The starfish can move on an obstacle-free surface at a rate of about one foot per minute. *A. planci* has been observed to move over the sand bottom between reefs. There is no evidence to show whether the movement is random or, if directional, what environmental factors direct the movement.

3.5 The evidence suggests that the food of *A. planci* is confined to corals, that it prefers branching corals of the genus *Acropora*, that it avoids the fire-coral (*Millepora* spp.) unless other food is absent, and that if no hard corals are present it may attack soft corals.

3.6 When present on reefs in low densities the starfish are possibly active only at night and spend the daylight hours in dark nooks and crannies. But in dense populations they will continue feeding in strong daylight in quite shallow water.

The Nature of a Coral Reef

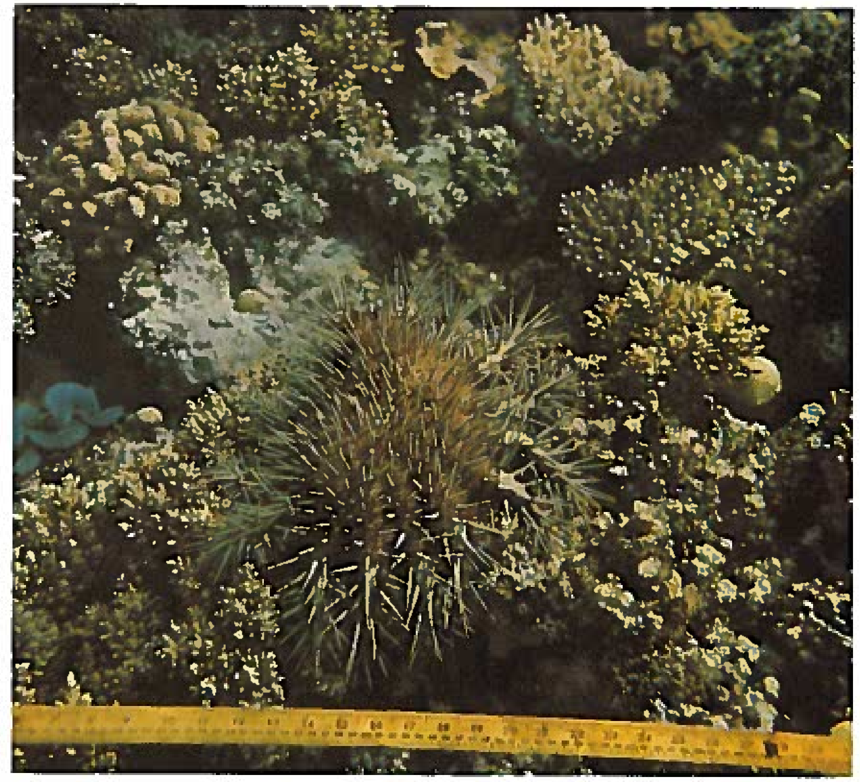
3.7 The physical structure that is called a coral reef comprises a vast amount of dead material on which exists a discontinuous outer layer of living material. Reef-building is performed not only by stony corals but also by a number of plant and animal species which share with coral the ability to secrete skeletons or shells of calcium carbonate. Hard corals play a critical part in the reef-building process by forming a nucleus about which other reef-builders aggregate. Lime-secreting algae contribute more to the total reef mass than corals. As the reef builds upwards towards the surface the earlier-formed growths are smothered or die from other causes and the reef is consolidated around their skeletons by infiltration of debris and by various physical and chemical processes. An outer layer of living coral grows luxuriantly on the reef down to a depth of 30–50 feet. Reef-building corals are confined to water receiving sufficient light for the needs of the symbiotic algae which live in the coral tissues.

3.8 The topmost layer of living coral does not cover the basic foundation completely. The proportion of the coral reef surface that is composed of living coral is never 100%; indeed, it is often very low. On the slopes on the outer edges of the reef, particularly on the weather side, the coral growths are generally denser than elsewhere. A reef flat is often mostly sand or rubble.

3.9 During cyclonic storms coral may be broken and this, with sand and other materials, may scour the reef to some extent. The waste material will settle after the storm and by compacting processes add to the dead bulk of the reef.

Theories Advanced for Increase in *A. planci* Population

3.10 Fundamentally the problem of the crown-of-thorns is one of population dynamics. Although fluctuating about an average value, the numbers of all species of organisms are kept at normal levels by a naturally evolved system of checks. When a greatly increased population is found it is natural to look for a failure of one or more of the normal checks. This, in essence, is the common feature of all the explanations



Photos: R. G. Pearson

Crown-of-thorns starfish, *Acanthaster planci*, feeding on hard corals, Lodestone Reef, 1970. The white area in the lower photograph indicates coral recently killed by the starfish.

this view has been that the known outbreaks have occurred close to centres of human habitation. However, the Committee is inclined to the view that outbreaks have been noticed first near centres of habitation because there are people there to see them. There is evidence of a number of outbreaks remote from any considerable centre of human population, and many areas of reef near human habitation do not seem to have been visited by crown-of-thorns starfish.

3.12 In an attempt to determine whether there had been previous infestations of *A. planci* on the Great Barrier Reef, the committee was assisted by Professor W. G. H. Maxwell. Reef debris obtained on a geological survey of the Queensland shelf was examined for echinoderm components. It was not possible to identify *A. planci* as such, but the major group to which it belongs was recognizable. Radiocarbon dates of two samples gave results consistent with ages of 830 ($\pm$80) years to 1500 ($\pm$100) years. Two other samples, previously analysed, gave ages of 250 and 390 ($\pm$80) years. Details of this work are included in Appendix G.

3.13 Predation to control an adult population may occur against eggs, larvae, or any stage of juvenile or adult forms. Most eggs and larvae fail to survive, so that the predatory and other destructive forces may be greatest in the early phases. It is therefore likely that any disturbance which leads to an increase of the adult population operates in favour of the survival of eggs and larvae. The predation of the adult is very rarely an effective way of reducing population in any high-fecundity species such as *A. planci*.

3.14 The Triton Theory.—The giant triton or giant trumpet shell (*Charonia tritonis*) has been observed in aquaria to eat the crown-of-thorns starfish and it has been suggested that the increase in the starfish population has been caused by heavy fishing of the triton on the Great Barrier Reef, reducing predator pressure. The Committee found no evidence to support this hypothesis. On the contrary, there are examples from reefs in other parts of the Pacific where there has been heavy fishing of the triton but no resulting increase in *A. planci* population. Some evidence was offered of the large trade in giant trumpet shells but further evidence disclosed that

(i) the majority of trumpet shells collected on the Great Barrier Reef were the false trumpet shell (*Megalatractus aruanus*); the giant triton was never very abundant;

(ii) the majority of giant triton shells offered in Australian souvenir shops are actually imported.

The Committee therefore considered, on the evidence, that this theory was not proven, and that collection of tritons appeared unlikely to be the prime cause of the increase in starfish population.

3.15 The Pollution Theory.—Polychlorbiphenyls (PCB), a group of plastic solvents, have been found in high concentration in gonads of *Acanthaster* on a reef at Guam, and theories have been advanced that this substance and various pesticides might be washing into the Barrier Reef waters and in some way interfering with the normal

dilution factor when the river waters enter the sea would make effects in sea water even less likely.

3.16 There are two processes which might counteract this. Firstly, there is some evidence of pesticide concentration in surface wind slicks on the air/water interface. Whether this is purely physical or (more likely) a phenomenon associated with surface phytoplankton is unknown. Secondly, it is now well established that some organisms accumulate persistent pesticides in their tissues to levels well above that in the outside environment.

3.17 The Committee was able (by courtesy of Mr. W. McCray, of the Queensland Department of Primary Industries) to have samples of starfish, clam, and coral material analysed for the presence of PCB and several pesticides known to be used in agriculture in the adjacent parts of Queensland. The samples came from reefs with large *Acanthaster* populations.

3.18 The results showed that the amounts of these substances present were insignificant. These observations do not support the theory that these chemicals are the cause of the apparent increase in the numbers of starfish. The relevant report by Mr. D. J. Tranter is included as Appendix F.

3.19 The Painted Shrimp (*Hymenocera elegans*).—This shrimp has been observed by Dr. Wickler of the Max Planck Institute to feed on gonads of *A. planci*. It has been suggested that *H. elegans* may be a predator of the starfish but this has not been established in the natural environment. There is no evidence on the current or former population levels of the shrimp, nor have there been any tests to ascertain whether the shrimp in fact feeds on *Acanthaster* when a variety of other foods is available. The supposed diminution in numbers of shrimp has been linked with the pollution theory by the suggestion that feeding on the pesticide-loaded gonads of the starfish would kill the shrimp. There is a complete lack of evidence to support the hypothesis.

3.20 The Blasting or Dredging Theory.—The natural coral reef is populated by many species of filter-feeding animals and corals, all of which could be consumers of starfish larvae. Areas cleaned of these reef animals by explosives or dredging would leave an unoccupied surface where larval starfish could settle unharmed by feeding animals of the ocean bed (benthic feeders). From such a focus of settlement the crown-of-thorns could move to the living reef.

3.21 During World War II far greater damage was done to reefs by explosives and dredging than has been done by civilian enterprises or military testing since, but reports of abnormally large populations of the starfish were not received until the 1950s. Also, many centres of abnormal occurrence had not been subjected to reef clearing, and other areas where reefs had been dredged or blown up did not produce large populations. The question must also be asked whether such a happening would allow other organisms, as well as *Acanthaster*, to survive in unprecedented numbers.

3.22 The inference in the theory that benthic animals are a major predator of

3.23 Predatory Fish.—There have been some reports of fish eating adult crown-of-thorns starfish but there is no knowledge of whether fish ingest the larvae. It does not appear that predation by fish is a significant factor in controlling the population of *A. planci*.

3.24 The Change of Environment Theory.—There have been suggestions that the population balance of this starfish may have been upset by a change in the physical or chemical environment. There is evidence of a rise in the mean annual temperature of the western Pacific Ocean just prior to the first records of the *Acanthaster* increase. It is difficult to conceive how such a change could influence population numbers, except perhaps by hastening the larval period and hence increasing the survival rate at settlement. If this did occur, it is surprising that other species did not also show a change in population.

3.25 The Mutation Theory.—It has been suggested that a change in the genetic composition of *Acanthaster* may have produced a strain better adapted to its animate and/or physico-chemical environment and that as a result the great increase in numbers has occurred. It was further suggested that unless mutations also occur amongst the predators of the starfish, the large population will continue as long as its members can find suitable food. The probability that a particular mutation happened simultaneously over widely separated areas in the Indo-Pacific region and became dominant in all of the subpopulations is so slight that the theory cannot be given serious thought. Also the approximate contemporaneity of population increases over such a vast area does not lend credence to any theory of a successfully established mutation spreading from some locus.

3.26 The Periodic Fluctuation Theory.—The phenomenon of good and bad brood years is well known in many marine populations, including fish, molluscs, and other starfish. Population levels are controlled by a number of factors such as predators of larvae, juveniles, or adults, availability of food at each stage, parasites of each stage, variable fecundity, success in spawning, and the physico-chemical environment. Periodically all the factors may be favourable and a large population will survive to adulthood. The Committee was informed of increases in *Acanthaster* populations earlier in the century. Dana (1970) has drawn attention to records which suggest large populations in various parts of the Indo-Pacific region in earlier times. If the present large population is the result of such a combination of circumstances it can be expected to decrease in subsequent generations.

4. SUMMARY OF EVIDENCE

Density of Starfish Populations

4.1 The first report of *A. planci* on the Great Barrier Reef was by Clark (1921).

4.2 Although specialized underwater collecting was being carried out on reefs near Cairns and Townsville in the early 1960s, no large concentrations of the crown-of-thorns starfish were noticed until 1964. Since 1965 there have been numerous records of the starfish, sometimes in large numbers, particularly in the general area between Cooktown and Townsville. A little over two hundred estimates of the population of *A. planci* on reefs have been made in the period 1966–70 by six groups. Some of these were made on the same reefs at different times. The proportion of the reefs of the Great Barrier Reef actually inspected is less than 10%. Of the 92 reefs visited by Mr. Pearson up to August 1969, only 23 had a high density population of *A. planci* (i.e. more than 40 counted in 20 minutes). The surveys include reefs from the southern end of the Reef to Lizard Island in the north. Reefs north of Lizard Island have recently been visited by Vine (1970) and by Woodhead and Weber (1970) who found little evidence of *A. planci* activity.

4.3 The sampling method adopted by the Pearson–Endean investigation was to swim, equipped with face mask and snorkel, counting the number of starfish seen in a known time. Twenty minutes was aimed at, but the swims varied between 5 and 310 minutes; all records were expressed in terms of the number counted in 20 minutes as compared with the number per 100 minutes for the Endean report (1969). The counts extended to a depth of only about 30 feet and covered about 1000 square metres, being 200 metres by 5 metres scanned in 20 minutes. Areas of abundant coral growth were selected. In most cases only the northern and southern tips of the reef were surveyed. Thus for an average reef, approximately 10 miles in circumference, about 2 or 3% of the reef was surveyed.

4.4 This indicates that extrapolations on the condition of reefs were being made from counts made on 2 or 3% of the area, selected for coral abundance and by location at the northern and southern tips. When the Committee visited Lodestone Reef, the only dense concentrations of the starfish apparent were at the north-east tip of the reef; any extrapolation from surveys on this part of the reef would have been misleading in assessing the general condition of Lodestone Reef.

4.5 Mr. Laxton, who carried out observations on starfish density during 1970, employed a different technique. He used a transect line of 100 metres and counted all crown-of-thorns starfish in a band 2 metres on each side of the line, thus obtaining counts in a 400-square-metre area. He has counted on Lodestone Reef in the area of densest occurrence of the starfish. His estimate agrees well with Mr. Pearson's estimate for the same area made four weeks later.

4.6 The difficulties and dangers of estimating starfish numbers from small samples are illustrated by figures quoted for Lodestone Reef. In June 1970 Dr. Endean made a statement in a television interview and was quoted in the press as having calculated that there was a population of 3,000,000 starfish on Lodestone Reef. The next day he corrected this to 300,000. A few weeks later the Committee visited Lodestone and

4.7 The position may be summarized by stating that the difficulties of sampling during surveys mean that the available methods of estimating population densities of *A. planci* are rather crude. Extrapolations from these results are not reliable and are of doubtful value. Large areas of a reef must be surveyed before it can be decided whether or not an abnormal situation exists.

4.8 Evidence, including photographic material, was given that at their densest the crown-of-thorns starfish were massed against one another. The Committee witnessed such a group in one isolated section of Lodestone Reef. The greatest density of starfish reported to the Committee was on a small fringing reef of the Frankland Islands (a count of 405 in 5 minutes). Other high counts were 888 in 20 minutes at Green Island and 928 in 20 minutes on Fitzroy Island reef.

4.9 In common with many other marine organisms, starfish occur in patches and are less obvious by day than they are by night. However, the opinion was expressed to the Committee that in high densities the starfish lose their sensitivity to light and under these circumstances, daylight counts of starfish would be reasonably accurate.

4.10 Two claims were made to the Committee that unusually large numbers of the crown-of-thorns starfish had been seen on the Great Barrier Reef—one shortly after World War I and the other about 1954. Recently Dana (1970) reviewed earlier reports of large numbers of *A. planci* from other parts of the Indo-Pacific.

Potential for Future Increase

4.11 It has been claimed that the population of adult *A. planci* is continually increasing; juvenile starfish have been recorded on reefs off Townsville, indicating that successful settlement of young continues. However, as simultaneous surveys of all affected reefs have not been made, it is impossible to substantiate the claim of an increase. Given the breeding potential of the species, there may well be new infestations in the future on reefs previously untouched. Nevertheless, this cannot be accepted as inevitable, for it is well established in marine biology that a large adult population of high fecundity does not necessarily ensure a high rate of recruitment. Conversely, a small adult population does not necessarily mean a low rate of recruitment. In other words, the potential for a large infesting population is always present, given the right combination of circumstances.

Extent of Starfish Damage

4.12 The evidence is clear that the damage on certain reefs has been severe. Estimates have been made that on particular reefs, up to 99% of the coral has been killed by *A. planci* (Endean 1969). The Committee is not entirely convinced that all such claims are correct because the methodology, particularly that used up to the end of 1969, is suspect. The sites for counting were not selected at random, but were on the tips of

by snorkelling or by inspecting the reefs through a glass-bottomed box. This was regarded as an approximate method by those using it and by others.

4.14 The method of selection of survey areas might also lead to invalid extrapolations. In July the Committee examined Lodestone Reef immediately before a public statement was made that the corals on that reef were almost entirely eaten out. This was not true at the time of the Committee's visit. Although extensive damage was evident in water deeper than about 15 feet, in most parts of the reef the corals in shallower water were flourishing. Soon after the public statement, a party of Townsville skin-divers confirmed that the condition of the reef was still as the Committee had found it.

4.15 Subsequently Mr. Laxton adopted more precise survey methods. By scuba diving and laying down a quadrat frame, more accurate visual estimations can be made of the proportion of the bottom covered by dead coral, supplemented by photographs of the sample area for later analysis.

4.16 Large concentrations of crown-of-thorns starfish have been found near coral whose white appearance indicated that it had been recently killed, leaving little doubt that the starfish was responsible. There are some cases where observations on the coral before and during infestation have demonstrated that the starfish were responsible for killing a high proportion of the coral which was alive at the time of the first inspection. In other reefs the evidence was circumstantial, but the witnesses were confident from the appearance of the dead coral that the crown-of-thorns starfish had been responsible for most of the recent deaths.

4.17 What is lacking from the reports made available to the Committee is any record of the amount of dead standing coral before the starfish moved in. All witnesses agreed that a normal coral reef, without a starfish infestation, includes an amount of dead standing coral which varies from reef to reef, estimates ranging from about 10 to 50%. Siltation has sometimes been responsible for a higher proportion being killed. In normal circumstances dead coral is least abundant on the reef slope and most abundant on the reef flat.

4.18 Some of these dead corals may have resulted from a previous invasion of the starfish, but other factors such as low salinity, cold, smothering, and predators other than *A. planci* are known to cause coral destruction. Such destructive factors cannot be confused with those of a cyclone which leave little coral standing alive or dead.

4.19 The published figures on the proportion of dead coral on reefs attacked by the starfish have included the estimated 10 to 50% of corals killed by other means.

4.20 The depredations of the starfish affect corals in the first instance, but the view is widely held that the associated fauna is also affected. However, there is no evidence that the reef fish are seriously affected, at least in biomass.

Recovery of Reefs

4.22 Several witnesses were of the opinion that both the kinds and variety of fish on a devastated reef have changed; but even in the Cairns–Innisfail area where the reefs are alleged to have been seriously affected, the commercial catch has neither diminished nor changed in composition. Some witnesses claimed that many of the fish use the dead standing coral for shelter as effectively as live coral. However, certain species of fish feed on corals and presumably their numbers would diminish on a severely damaged reef.

4.23 In terms of corals alone, two processes contribute to reef recovery. Firstly, regeneration, i.e. recommencement of growth of a coral colony from living foci which the starfish missed. This is mainly seen in branching forms like *Acropora*, where tips in particular may survive, and in massive corals such as *Porites*. Secondly, recovery is dependent on recolonization, i.e. new corals settling from a free-living planktonic larval form.

4.24 Fears have been expressed that the destruction of regenerating colonies has only been deferred, as the standing dead parts of the colony will sooner or later collapse and the regenerating live tips would smother. There is no evidence of the likely period involved before collapse, which presumably would be more likely on the exposed weather side of reefs. Other witnesses, however, have disputed the conclusion that smothering is inevitable and claim that a high proportion of regenerating corals will continue to grow successfully even if the colony's base collapses. It should be noted that the bases of a large proportion of living coral colonies are dead. No evidence of the relative strength of dead and live coral colonies has been produced.

4.25 Regeneration varies from reef to reef. The Committee itself noted wide variety in the proportion of regenerating tips from one reef to another. Regeneration is known to be effective for certain species. No evidence was obtained that it is effective for the majority of species.

4.26 The greater part of coral recovery depends upon recolonization. Evidence was given that within a few weeks of widespread killing the dead standing coral becomes matted with algae which could prevent coral larvae from finding a suitable firm substrate for settlement. However, there is doubt as to how long this algal cover persists and whether it inhibits coral settlement.

4.27 Evidence was given that soft corals have settled widely and grown rapidly on at least some of the devastated reefs and fears have been expressed that these soft corals would effectively prevent larvae of hard corals from settling. Again, other witnesses have suggested that the life span of soft coral is short, so that even with a dense cover of soft coral, settlement of more desirable species would only be delayed. On the reefs seriously affected by *A. planci* visited by the Committee, the area covered by soft corals was comparatively small.

4.28 Some witnesses expressed the view that particular reefs would not recover

larvae could drift over 150 miles and settle on damaged reefs. This applies to the larval forms of the great majority of the species of organisms which make up the reef ecosystem, so that the loss of any species from a particular reef does not preclude that species' re-establishment on the reef.

4.29 Widely differing views have been expressed on the actual rate of recovery and on the diversity of recolonizing species. To some extent these differences arise from differences in methodology. Published statements claiming only a 1% recovery on several reefs were not based on the percentage of area covered by recolonized coral, but on the number of colonies per square metre. Expression of this as a percentage is meaningless since one colony could, in time, cover the entire square metre. Other workers, recognizing this, have measured the percentage area covered by recolonizing corals.

4.30 Being aware of the importance of regeneration and recolonization, the Committee commissioned Associate Professor P. M. J. Woodhead to survey and compare reefs damaged by starfish and by a cyclone. Professor Woodhead is a marine biologist with specialized knowledge of coral. Prior to his departure from Heron Island Research Station at the end of 1969, he had been conducting experiments and making observations on coral regrowth in an area of Heron Reef where the coral had been almost completely destroyed by a cyclone in January 1967. He revisited this area in June 1970 and spent several days conducting quadrat surveys of selected areas of Green Island Reef and Feather Reef where there had been extensive damage by starfish. During these quadrat surveys he counted the number of colonies of coral, measured the area covered, and also identified the species.

4.31 Professor Woodhead found that in the three and a half years since the cyclone considerable recovery of coral had occurred on Heron Reef. Comparable regrowth had occurred also on the southern corner of Green Island Reef in terms of living coral cover and numbers of living coral colonies and in diversity of species. This area also compared well with Low Isles and Nymph Reefs which had not suffered recent damage by cyclones or starfish. The situation on other areas of Green Island Reef was not as advanced but Professor Woodhead noted that corals in these areas would be less luxuriant even under normal conditions because of the less favourable environment. At Feather Reef recolonization had not proceeded far in the two areas examined, but it is not known when *A. planci* left these parts. A report prepared by Professor Woodhead is included in this Report as Appendix E.

4.32 Professor Woodhead also reported to the Committee on his experiments on coral growth rates which he had prepared on Heron Island. These results are important to the question of the rate of recovery of damaged reefs and are included in Appendix D. They show a wide variation between species and also the general decrease of growth rates with depth.

5. FURTHER RESEARCH

with more circumspection and with less public alarm only if there is greater knowledge and understanding of all aspects of the problem.

5.2 The Committee recommends that research should be undertaken particularly into

(i) reef ecology, with particular attention to the biology of *A. planci* and corals;

(ii) continued monitoring of *A. planci* populations;

(iii) experiments in local control of *A. planci.*

5.3 This research should be initiated as soon as possible because of the opportunity that now exists to study reefs under attack by the starfish and to observe the recovery of the reefs from recent damage. The research should not be delayed until the Australian Institute of Marine Science is functioning at Townsville. This will not occur for some time and the present starfish situation may not then obtain. Nevertheless, it is hoped that the interests of the Australian Institute of Marine Science will include *A. planci* and coral on the Great Barrier Reef.

Scope of Research

5.4 Biology of *A. planci.*—This study should be directed towards establishing duration of larval life; pattern and distance of larval dispersal; aggregation of larvae; rate and causes of mortality (predation, physico-chemical factors); settlement behaviour and influences; metamorphosis, mortality, and behaviour of juveniles; food requirements at all stages; migration ability; aspects of reproduction and genetics.

5.5 Biology of Corals.—Selected species should be studied with respect to growth rates, reproduction, larval duration, patterns and distance of dispersal, larval and adult mortality, and settlement.

5.6 Reef Ecology.—Research should be undertaken on species succession in re-colonization; variation in fish biomass and composition resulting from reef damage; the nature of distribution, the food web, and other relationships of reef organisms.

5.7 Control.—Decisions on possible long-term control are dependent on the results of some of the research listed above. Experiments in local control measures should be carried out in selected areas (including tourist resorts). Preliminary results from Japanese tests using copper sulphate unigel mixtures are sufficiently encouraging to warrant further trials in reef waters. Experiments on other bulk extermination methods should also be undertaken.

5.8 Coordination of Research.—Cooperation between all workers in this research should be encouraged in order that maximum interchange of information and ideas may be achieved, unnecessary duplication of effort avoided, and full utilization of facilities ensured. Specific direction of research projects by administrators is not

Priorities in Research

5.9 Survey of the Occurrence of the Crown-of-thorns Starfish and Subsequent Monitoring.—The geographic limits of the large populations of starfish are unknown, as is the variation in population density within the present known areas of occurrence. This is basic to an understanding of the magnitude of the problem. It is essential that subsequent changes in population level be monitored to provide information on possible future distribution of the organism on the Great Barrier Reef.

5.10 Study of the Reproduction, Larval Life, and Larval Settlement of the Starfish.—The evidence points to the settlement, subsequent metamorphosis, and early juvenile life as crucial in determining population numbers. No convincing evidence was produced of a natural control mechanism operating on the adults. On the contrary, numerous instances were given of marine populations fluctuating according to the level of larval survival.

5.11 Study of Coral Recolonization of Affected Reefs.—This is necessary before answering the question of how long a reef takes to recover. The recovery of some reefs, or parts of reefs, has been better than others. There is virtually no knowledge of the possible inhibitory effects of either algal cover or soft coral growth. Whether there is any pattern of natural succession in subsequent coral colonization is unknown.

5.12 Mass Control Measures.—Control measures being used elsewhere in the Pacific depend on injection or hand-picking of individual starfish. Mass control methods should be more economical. Professor Suyehiro's method (see 5.7) might be investigated to determine its effectiveness in preventing invasion of particular reef areas. This would involve the laying on the adjacent sea-floor of a perforated Nylex tube from which copper sulphate slowly escaped.

Proposals for Implementation of Research

5.13 In order to assist in implementing the proposals for further research, the Committee makes the following recommendations to the Commonwealth and Queensland Governments:

(i) That a Research Trust Fund be established by the two Governments.

(ii) That an Advisory Committee of not more than five members be appointed by the Governments to recommend allocations from the Trust Fund.

(iii) That present or future research projects on *A. planci* or coral undertaken by the Queensland Department of Primary Industries be financed from the Research Trust Fund with the approval of the Advisory Committee.

(iv) That the Advisory Committee be empowered to recommend grants-in-aid for research and contracts for work in specific areas.

(vi) That these recommendations apply for an initial period of three years and be extended subject to a review of the existing needs for further research in the field, having regard to the development and interest of the Australian Institute of Marine Science.

(vii) That all projects involving international cooperation and requiring Government financial assistance or requiring invocation of the United States–Australian Agreement on Scientific Collaboration be referred to the Advisory Committee.

(viii) That a sum of money of the order of $90,000–$120,000 be provided in the first year for the Research Trust Fund and that the sum provided be increased progressively by $20,000 in each of the second and third years.

APPENDIX A

Persons who appeared before the Committee

Dr. R. Endean, Department of Zoology, University of Queensland
Mr. G. G. T. Harrison, Department of Primary Industries, Queensland
Associate Professor P. M. J. Woodhead, Marine Sciences Research Laboratory, Memorial University of Newfoundland, Canada
Professor Dorothy Hill, Department of Geology, University of Queensland
Dr. R. H. Chesher, Westinghouse Ocean Research Laboratory, Miami, U.S.A.
Dr. I. Eibl-Eibesfeldt, Max Planck Institute for Behavioural Physiology, West Germany
Mr. Theo W. Brown, Sydney
Associate Professor A. K. O'Gower, School of Zoology, University of New South Wales
Dr. F. H. Talbot, The Australian Museum, Sydney
Dr. M. F. Day, Member of Executive, CSIRO, Canberra
Mr. V. N. Vlasoff, Cairns
Professor C. Burdon-Jones, James Cook University of Townsville, Queensland
Dr. G. D. Broadbent, Townsville
Mr. A. Miller, Cairns
Mr. R. Cantley, Magnetic Island, Queensland
Mr. D. Tarca, Townsville
Mr. E. Gibson, Townsville
Mr. Ben Cropp, Southport, Queensland
Mr. E. M. Grant, Fisheries Branch, Department of Primary Industries, Queensland
Professor W. Stephenson, Department of Zoology, University of Queensland
Mr. R. G. Pearson, Fisheries Branch, Department of Primary Industries, Queensland
Mr. N. M. Haysom, Fisheries Branch, Department of Primary Industries, Queensland
Mr. J. H. Laxton, Department of Zoology, University of Queensland
Miss Julia Henderson, Fisheries Branch, Department of Primary Industries, Queensland
Dr. D. F. McMichael, National Parks and Wildlife Service of New South Wales
Miss Elizabeth Pope, The Australian Museum, Sydney
Dr. B. R. Wilson, Western Australian Museum
Dr. D. F. Waterhouse, Division of Entomology, CSIRO, Canberra
Professor J. W. Wells, Department of Geological Sciences, Cornell University, U.S.A.

APPENDIX B

Individuals and Organizations who made Written Submissions to the Committee

Mr. E. B. Bremner, St. Ives, N.S.W.
Mr. Theo W. Brown, Sydney
Professor C. Burdon-Jones, James Cook University of Townsville, Queensland
Mr. W. G. Cargill, Bardon, Queensland
Dr. R. Endean, University of Queensland
Mr. E. M. Grant, Department of Primary Industries, Queensland
Mr. G. G. T. Harrison, Department of Primary Industries, Queensland
Mr. N. M. Haysom, Department of Primary Industries, Queensland
Professor Dorothy Hill, Department of Geology, University of Queensland
Mr. D. R. L. Justelius, Collaroy Beach, N.S.W.
Associate Professor W. G. H. Maxwell, Department of Geology and Geophysics, University of Sydney
Dr. D. F. McMichael, National Parks and Wildlife Service of New South Wales
Mr. P. Michell, East Brighton, Victoria
Mr. R. Pearson, Department of Primary Industries, Queensland
Miss Elizabeth Pope, The Australian Museum, Sydney
Mr. R. Pullen, Inala, Queensland
Mr. E. S. Scott-Holland, Mosman, N.S.W.
Dr. Y. Suyehiro, Keikyu Abura Asubo Marine Park Museum, Japan
Dr. F. H. Talbot, The Australian Museum, Sydney
Mr. D. J. Tranter, Division of Fisheries and Oceanography, CSIRO, Cronulla, N.S.W.
Dr. N. Wickler, Max Planck Institute for Behavioural Physiology, West Germany
Dr. B. R. Wilson, Western Australian Museum, Perth, W.A.
Associate Professor P. M. J. Woodhead, Marine Sciences Research Laboratory, Memorial University of Newfoundland, Canada

S.C.U.B.A. Divers Association of Australia
The Great Barrier Reef Committee

APPENDIX C

Documents and Articles referred to by the Committee

Australian Conservation Foundation (1969).—The future of the Great Barrier Reef. Spec. Publ. No. 3.
Barnes, J., and Endean, R.—A dangerous starfish—*Acanthaster planci* (Linné). *Med. J. Aust.* **1964**(I), 592.
Beau, A. G. (1970).—The Mollusca of the genus *Charonia*. *Trans. Roy. Soc. N.Z.* **11**, 16.
Boshoff, P. H. (1958).—Development and construction of the coral reefs. In 'A National History of Inhaca Island, Moçambique', ed. W. Macnae and M. Kalk. (Witwatersrand Univ. Press.)
Broadbent, G. D. (1968).—Ciguatera in Queensland. South Pacific Commission Seminar on Ichthyosarcotoxism, 1968.
Burkenroad, M. D. (1957).—Intensity of setting of starfish in Long Island Sound in relation to fluctuations of the stock of adult starfish and in the setting of oysters. *Ecology* **38**(1), 164–5.
Campbell, A. C. (1970).—Communication concerning Cambridge Expedition to Red Sea.
Campbell, A. C., and Ormond, R. F. G. (1970).—The threat of the crown-of-thorns starfish (*Acanthaster planci*) to coral reefs in the Indo-Pacific area: observations on a normal population in the Red Sea. *Biol. Conserv.* **2**(4), 246–51.
Cantley, R. (1970).—Correspondence relating to crown-of-thorns starfish and estuarine pollution in the Great Barrier Reef.
Chesher, R. H. (1969).—Destruction of Pacific corals by the sea star *Acanthaster planci*. *Science* **165**, 280–3.
Chesher, R. H. (1969).—*Acanthaster planci*: impact on Pacific coral reefs. Report (abridged) from Westinghouse Res. Lab. to U.S. Dep. Interior.
Chesher, R. H. (1970).—*Science* **167**, 1275.
Clark, H. L. (1921).—The echinoderm fauna of Torres Strait: its composition and its origin. Publs Carnegie Inst. Washington No. 214, 101.
Coping with *Acanthaster*. *Nature* **228**, 1970, 12.
Crown-of-thorns not so fatal. *Nature* **227**, 1970, 5.
Dana, T. F. (1970).—*Acanthaster*: a rarity in the past? *Science* **169**, 894.
Ellis, J., and Solander, D. (1786).—'The Natural History of Many Curious and Uncommon Zoophytes collected from Various Parts of the Globe.'
Endean, R. (1961).—Queensland faunistic records (Pt VII), I (13). (Univ. Queensland Press.)
Endean, R. (1969).—Report on studies on the crown-of-thorns starfish *Acanthaster planci*.
Fairbridge, R. W. (1950).—Recent and Pleistocene coral reefs of Australia. *J. Geol.* **58**(4), 330–401.
Fischer, J. L. (1969).—Starfish infestation: hypothesis. *Science* **165**, 645.
Galtsoff, P. S., and Loosanoff, V. L. (1939).—Natural history and method of controlling the starfish. U.S. Bur. Fish. Bull. **49**(3), 75–132.
Goreau, T. F. (1961).—Problems of growth and calcium deposition in reef corals. *Endeavour*, Jan., 32–9.
Goreau, T. F. (1969).—The *Acanthaster* survey of Saipan, Mariana Islands: structure and ecology of the Saipan reefs in relation to predation by *Acanthaster planci*.
Hedley, C. (1925).—The natural destruction of a coral reef. Rep. Great Barrier Reef Committee, Vol. 1, No. 3, 35–40.
Helfrich, P., and Banner, A. H. (1968).—Ciguatera fish poisoning. II. General patterns of development in the Pacific. Occ. Pap. Bernice P. Bishop Mus. **23**(14).
Helfrich, P., Piyakarnchana, T., and Miles, P. S. (1968).—Ciguatera fish poisoning. I. The ecology of ciguateric reef fishes in the Line Islands. Occ. Pap. Bernice P. Bishop Mus. **23**(14).

Lee, C. F. (1948).—Technological studies of the starfish. 1. Starfish control—its economic necessity and methods used. *Comml Fish. Rev.* **10**(1), 1–6.

Lee, C. F. (1955).—An analysis of starfish control measures as practised by oystermen. *Natn. Fisherm.* 36(4), 19–20.

Loosanoff, V. L. (1961).—Biology and methods of controlling the starfish, *Asterias forbesi* (Desor). U.S. Bur. Comml Fish. Fishery Leafl. 520.

Loosanoff, V. L., and Engle, J. B. (1938).—Chemical control of starfish. *Science* **88**, 107–8.

Loosanoff, V. L., and Engle, J. B. (1942).—Use of lime in controlling starfish. U.S. Fish Wildl. Serv. Res. Dep. 2, 1–29.

Madsen, F. J. (1955).—A note on the sea star genus *Acanthaster*. *Vidensk. Meddr dansk naturh. Foren.* **117**, 179–92.

Maxwell, W. G. H. (1968).—Relict sediments, Queensland continental shelf. *Aust. J. Sci.* **31**, 85.

Maxwell, W. G. H. (1969).—The structure and development of the Great Barrier Reef. In 'Essays in Honour of Dorothy Hill'. (A.N.U. Press, Canberra.)

Mortensen, Th. (1931).—Contributions to the study of the development and larval forms of echinoderms, I–II.

Needler, A. W. H.—Quicklime for destroying starfish on oyster grounds. Prog. Rep. Atlantic Biol. Stn. 27, Note 74, 13–14.

Newman, W. A. (1970).—*Science* **167**, 1274–5.

Paine, R. T. (1969).—A note on trophic complexity and community stability. (Aust. Acad. Sci., Canberra.)

Palmieri, V. (1970).—Report on examination of fossil and subfossil samples from the Great Barrier Reef area to determine the presence of remains of *Acanthaster planci*. Geol. Surv. Qld.

Pearson, R.—Studies on the crown-of-thorns starfish on the Great Barrier Reef. Queensland Littoral Soc. Newsletter, Jan.–Feb. 1970, 1–10.

Pearson, R. G., and Endean, R. (1969).—A preliminary study of the coral predator *Acanthaster planci* (L.) on the Great Barrier Reef. Fisheries Notes, Dept. Harbours and Marine, Queensland, 3 (1), 27–55.

Phipps, C. V. G., Kendall, C. G. S., Goodwin, R., and Barbrick, C.—Report on Cruise of M.V. 'Matthew Flinders' through the Great Barrier Reef, August–September 1969.

Randall, J. E. (1958).—A review of ciguatera, tropical fish poisoning, with a tentative explanation of its cause. *Bull. mar Sci. Gulf Caribb.* **8**, 236–67.

Randall, J. E. (1968).—Marine algae as a possible source of ciguatera toxins. South Pacific Commission Seminar on Ichthyosarcotoxism, 1968.

Rapson, A. M. (1970).—Coral reefs—'the living reef'. (Personal communication.)

Roads, C. H. (1970).—Report on the 1969 Red Sea expedition of the Cambridge Coral Starfish Research Group into the starfish *Acanthaster planci*.

Scheltema, R. S. (1968).—Dispersal of larvae by equatorial ocean currents and its importance to the zoogeography of shoal-water tropical species. *Nature* **217**, 1159–62.

Thorson, G. (1950).—Reproductive and larval ecology of invertebrates. *Biol. Rev.* **25**, 35–8.

Vine, P. J. (1970).—Laboratory observations of the crown-of-thorns, *Acanthaster planci*. *Nature* **228**, 341–2.

Walne, P. R.—Destruction of competitive organisms on artificial oyster-spat collectors. *J. Cons. perm. int. Explor. Mer* **22**, 75–6.

Walsh, R. J. (1970).—Communication on *Acanthaster planci* in New Guinea.

Weber, J. N., and Woodhead, P. M. J. (1970).—Ecological studies of the coral predator *Acanthaster planci* in the South Pacific. *Marine Biol.* 6(1), 12–17.

Wells, J. W. (1957).—Coral reefs. *Mem. Geol. Soc. Am.* 67(1), 609–31.

Wickler, W., and Seibt, U. (1970).—Das Verhalten von *Hymenocera picta* Dana, einer Seesterne fressenden Garnele (Decapoda, Natantia, Gnathophyllidae). [The behaviour of *Hymenocera picta* Dana, a starfish-eating shrimp (Decapoda, Natantia, Gnathophyllidae).] *Z. Tierpsychol.*

APPENDIX D

The Growth and Normal Distribution of Reef Corals*

By Associate Professor P. M. J. Woodhead, Marine Sciences Research Laboratory, Memorial University of Newfoundland, St. John's, Canada. (July 1970.)

Coral Growth Experiments

When I first met the Committee I submitted measurements for the annual growth in *weight* on some of the commoner reef corals at Heron Island. Discussing the data, the Committee asked for details of growth in *size* of the corals. Measurements of average annual increments in weight, height, greatest horizontal diameter (D1), and the horizontal diameter at right angles to this (D2), are given in Table 1.†

Table 1.—Coral Growth Increments on Heron Island Reef—Growth at Surface (Reef Flat) 1968–69 (12 Months)

Species	No.	Wt. % Incr.*	No.	Height	Diam. D1	Diam. D2
Pocillopora damicornis	13	173 ± 28	10	18·4 ± 3·7	33·8 ± 3·7	38·9 ± 6·5
Porites andrewsi	17	123 ± 20	17	15·1 ± 2·6	29·5 ± 3·9	28·4 ± 3·2
Porites lutea	12	62 ± 9	13	11·3 ± 1·8	14·4 ± 2·4	16·6 ± 3·3
Pavona decussata	18	161 ± 17	18	18·0 ± 1·4	34·2 ± 2·9	31·2 ± 2·3
Psammocora gonagra	14	64 ± 10	15	7·3 ± 1·2	9·2 ± 1·7	9·1 ± 1·8
Acropora squamosa	16	324 ± 37	14	28·3 ± 2·6	68·8 ± 7·0	57·1 ± 7·8
Acropora formosa	14	160 ± 17	14	38·8 ± 5·0	71·1 ± 7·5	58·3 ± 8·7
Acropora hyacinthus	7	224 ± 61	7	32·0 ± 3·9	56·6 ± 13·9	56·1 ± 14·6
Acropora cuneata	5	42 ± 5	5	13·2 ± 2·4	16·6 ± 3·1	7·6 ± 2·3
Plesiastrea versipora	5	33 ± 11	6	9·2 ± 1·3	12·3 ± 1·8	6·6 ± 1·2
Goniastrea benhami	9	47 ± 7	10	5·2 ± 1·4	9·8 ± 1·2	8·2 ± 1·7
All *Acropora* spp.	41	216 ± 23				

* 'Wt. % incr.' is the increase in weight expressed as a percentage of the original weight.

During my visit to Heron Island Reef in June 1970, it was an aim to complete some experiments measuring effects of depth upon the rate of growth of some of the same common reef corals. The earlier experiments had suggested that growth rates were significantly reduced at a depth of 60 ft compared with growth at or near the surface and on the reef flat. The further experiments were set up to substantiate the apparent effect of depth and for this purpose growth in weight was considered the most sensitive index for comparison. The results for both the preliminary work of 1968–69 and the second experiment of 1969–70 are given in Table 2 (*a*) and (*b*), together with the ratios of the weight increase at 60 ft deep to that at the surface. The findings for the two periods are in accord.

It is apparent that depth has a marked effect in reducing the rates of growth of corals. This effect is clearly expressed in the distribution of corals on reefs (addendum to this section). It will also be significant in the recovery of reefs being recolonized after coral killing by *Acanthaster*. Nevertheless, the great bulk of living corals grow on the upper slopes of the reefs in shallow water, and from my own experience 60 ft is approximately the lower limit for the growth of significant colonies of reef frame-work forming corals on the Great Barrier Reef. This varies somewhat, however, especially with respect to water turbidity, but there seems to be no extensive reef-coral development much below 60 ft, with possible exceptions on the reefs of the Outer Barrier, where corals may grow well for perhaps 20 ft deeper.

This effect of depth upon coral growth has not been demonstrated previously and it is perhaps surprising that such a small change in depth should have so great an effect upon growth rates. Undoubtedly the depth effect operates through the reduction in 'photosynthetically useful' incident light, affecting the photosynthetic activity of the symbiotic zooxanthellae (microscopic algae) within the tissues of the corals (zooxanthellae have been shown to increase the rate of calcium carbonate deposition in corals about tenfold when photosynthetically active).

Table 2.—Coral Growth Increments (Weight) at Surface (Reef Flat) and at 60 ft Deep

Species	Depth (ft)	No.	Wt. % Incr.	Wt. % incr. at surface / Wt. % incr. at 60 ft
(*a*) Comparisons 1968–69 (12 months)				
Pocillopora damicornis	0	13	173±28	2·3
	60	4	76±18	
Porites lutea	0	13	62± 9	3·3
	60	5	19± 3	
Pavona decussata	0	18	161±17	1·4
	60	6	116±39	
Psammocora gonagra	0	15	64±10	1·4
	60	6	40± 8	
Goniastrea benhami	0	9	47± 7	2·1
	60	5	23±10	
(*b*) Comparisons 1969–70 (9 months)				
Porites lutea	0	5	42± 4	3·2
	60	6	13± 2	
Porites andrewsi	0	12	170±36	4·4
	60	10	39± 5	
Goniastrea benhami	0	10	26± 3	1·8
	60	7	14± 2	
Acropora squamosa		5	240±31	3·8
		8	63±21	

In conclusion, it is highly probable that the growth rates given in the tables are underestimates of normal growth, in that it would be expected that growth would be arrested for a time after colonies had been chiselled from their substrate and set in concrete. I should expect normal growth, without transplantation, to be faster.

I am grateful to the Committee for their support in the completion of this study, begun with the support of the Australian Research Grants Committee.

Addendum: Living Coral Distribution and Depth

In discussions of *Acanthaster* damage to corals, some comment has been made concerning dead coral on the deeper parts of the outer slopes of reefs. Since there is little information concerning changes in living coral cover with increasing depth on the Great Barrier Reef I have summarized some of my own quadrat-survey results for three reefs—Gannet Reef in the Swain Reefs complex, Low

10 fathoms and deeper. Nevertheless, there may be much dead coral at such depths, generally in the form of rubble swept down the reef slope.

I am grateful to the Belgian Expedition of 1967 and to the Australian Research Grants Committee for their support in obtaining the information in Table 3.

Table 3.—Living Coral Cover (as Percentage of Area) Changes with Depth

Depth (ft)	Coral Cover (%)	Sq-metre Quadrats
(*a*) SE. corner Low Island, fore-slope		
10	75	5
15–20	37	14
25–30	19	9
35–40	17	8
45–50	8	8
55–60	3	5
65+	No coral; fine sediments	
(*b*) SE. corner Gannet Reef, fore-slope		
10	50	5
15–20	64	5
25–30	12	5
35–40	16	5
45–50	12	5
55–60	3	5
65+	Widely scattered single colonies on sand	
(*c*) SE. end Lizard Island, fore-slope		
5	40	4
10–15	21	3
20–25	23	3
30–35	8	3
40–45	5	3
50–55	8	3
60–65	12	4
70	2	4
Deeper than 70 ft, a sand slope with occasional coral heads widely separated and isolated		

APPENDIX E

Surveys of Coral Recolonization on Reefs damaged by Starfish and by a Cyclone*

By Associate Professor P. M. J. Woodhead, Marine Sciences Research Laboratory, Memorial University of Newfoundland, St. John's, Canada. (July 1970.)

Short Expedition to Survey Reef-coral Recolonization and Regrowth

Personnel: P. M. J. Woodhead, R. Pearson, J. Broomfield.

Date: June 6–13, 1970.

Reefs surveyed: Heron (cyclone-damaged), Green (starfish-damaged), Feather (starfish-damaged).

Aims: (1) To survey coral recolonization and growth on Heron Reef, which was known to have been damaged by a cyclone at the end of January 1967. (2) To survey coral recolonization and growth on two reefs known to have been severely damaged by the crown-of-thorns starfish. Also, to make comparisons with Heron Reef in terms of recovery achieved.

Heron Reef

The northern side of Heron Reef (Capricorn Group) was severely damaged by a cyclone (code-name Dinah) on January 28 and 29, 1967, and thousands of tons of coral were torn from the slopes of the reef leaving large areas devoid of living coral. Typical areas were photographed about one week after the cyclone and one of these areas was used for the present surveys of coral recolonization and regrowth.

During the cyclone great seas pounded the reef, tearing off and smashing many coral heads; heads torn loose doubtless helped to batter remaining corals to a rubble.

After the cyclone there rapidly developed a very heavy growth of filamentous green seaweed (probably *Chlorodesmus*) over all of the areas destroyed, sediments settled with the seaweed, and together they formed a dense mat covering much of the coral rock. This seaweed-and-sediment mat dispersed slowly, but after a year the coral rock was largely clean and much had been covered by a pink cement of coralline algae; small numbers of new coral colonies had begun to settle. Resettlement and growth continued in subsequent years.

Present resurveys were made using square-metre quadrats, and measuring at every second metre along lines running parallel with the reef edge at depths of 10 to 15 feet. In each square metre the number of species, number of individual colonies, and total area covered by living coral were measured.

The final average figures per square metre for living coral found on the three surveys were:

	Mean Coral Cover	Mean No. Colonies	Mean No. Species
Survey A (P.M.J.W.)	27%	17	10
Survey B (P.M.J.W.)	24½%	17	9
Survey C (R.P.)	20%	14	9

All three surveys appear in good agreement; it should be noted that Survey C was shallower and nearer to the reef edge than A and B, although the difference was not great. A total of 1054 colonies was measured in the three surveys, giving an average colony size of about 1½% square metre.

Massive colonies such as *Porites*, *Favia*, *Favites*, and *Plesiastrea* are well represented. The species assemblage is quite typical for Heron Reef, virtually all species being common on other parts of the reef. Twenty-seven genera and subgenera of corals were seen during the surveys. On the basis of the surveys and data on coral growth at Heron Reef, it seems probable that the damaged slopes of the reef will be recolonized by well-grown colonies of corals ten years after the cyclone. In this respect it is interesting to mention a personal comment by Professor J. H. Connell, University of California. He had made some estimates of coral growth on Heron Reef and happened to return again just after the 1967 cyclone. One large head which he had marked and estimated to be about 20 years old had been killed on the north side of the reef and he pointed out that it had been twenty years since the last cyclone had struck this reef. The damaged areas were most certainly covered overall by very well-developed colonies prior to the cyclone in 1967 (my observations), and if we can assume that damage of the same order had been inflicted by the cyclone of twenty years previously (which seems likely), it can be concluded that in this situation the reef had effected complete recovery of corals in twenty years or less.

Green Island Reef

Green Island Reef suffered from heavy infestations of starfish in the early 1960s and a good account of the development and progress of the infestations has been given by Barnes (1966). The starfish became reduced in numbers on the reef during late 1966 and there were few by January 1967. They have not increased again since that time, and only three juveniles were found during the present surveys. Pearson (personal communication) found relative abundance* numbers in September 1966 of 1150 and 888; November 1966 of 100, 97, and 16; and January 1967 of 28, 7, and 1.

Four areas, in all of which Pearson had worked previously, were examined on Green Island Reef:

- (i) the 'back-reef' at the northern side of the main reef;
- (ii) the 'old' area used by the glass-bottomed boat trips (the 'old glassy patch'), which is area E in Barnes's report (1966);
- (iii) the reef slope at the southern corner, in the vicinity of Pearson's transect;
- (iv) the reef slope on the SW. side opposite the cay, near area B in Barnes's report.

(i) *North-side Survey*

The 'back-reef' area extended northward beyond the margins of the main reef flat. It was an area of rather loose coral growth over a sandy floor, with frequent rises of more compacted growth. This rising and falling topography varied in depth from 4 ft to 18 ft. I was reminded of the back-reef to the lee of Wilson Island (Capricorn Group), or the coral growth in the embayment on the leeward side of Lizard Island. The area had been heavily infested with starfish (Barnes 1966), although not all coral may have been killed according to Pearson. Only one quadrat survey was made, measuring every second square metre.

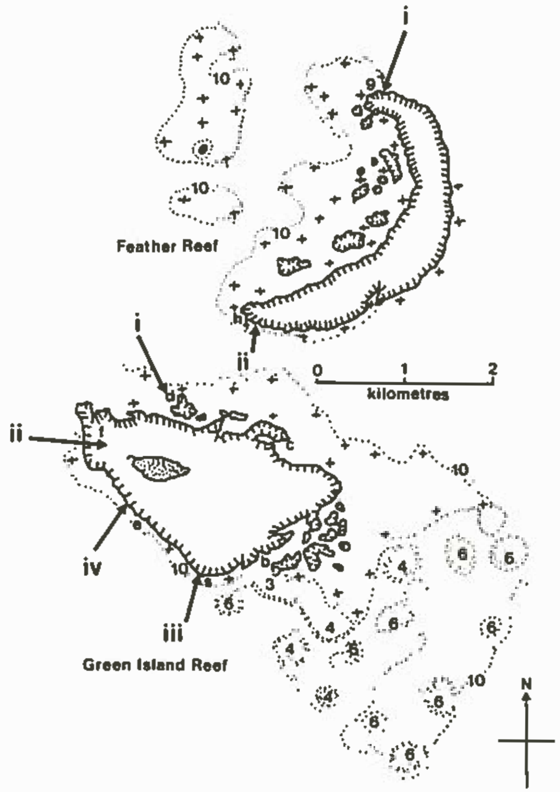
The average figures per square metre on this survey were:

Mean Coral Cover	Mean No. Colonies	Mean No. Species	Mean Area Soft
14%	5	2½	8%

The corals were always best developed at or near the tops of the rises, with many species represented. On the floor of the deeper areas there was much dead openly branching staghorn coral (principally *Acropora formosa*, but including other large species, such as *Acropora affinis*); there was also much living staghorn amongst this, and regrowth appeared well established. A dominant coral in these deeper areas was *Pocillopora damicornis*, a rapidly growing coral which occurred as frequent shrubby stands; from their size and distribution I considered that these colonies had

Bearing in mind firstly that this was a back-reef area, much of the coral lying openly above a sandy floor, very dense coral growth would not be expected. Indeed, the dead coral skeletons remaining showed clearly that earlier growth had been patchy and open. My conclusion was that the area was recovering well, and this was most marked on the periodic rises in topography. Although branching corals predominated, many massive corals such as *Favia* and *Platygyra* were common, although often still as small colonies. *Porites* colonies were common, often as large heads which had been only partially killed and appeared to be regrowing over the dead parts.

Soft corals were common in the back-reef region, but occupied a relatively small area. Considering that they are normally well represented in the back-reef environment they may not have been present in exceptionally high numbers.



Surveys, June 1970, indicated by arrows. (From Pearson's charts.)

(ii) *Old Glass-bottom Boat Patch, West of the Island, Survey*

No quantitative survey was made in this area. The greater part of the coral was dead and the water was very turbid. Many stands of dead staghorn coral were loose and could be moved by the waves; the bottom was largely sandy with rubble. This was the worst area seen on Green Island Reef with rather little evidence of permanent recovery. Many branches of staghorn, etc., had begun to regrow but were on insubstantial or loose bases. Many large heads of *Porites* and some *Goniopora* which had been only partially killed and appeared to be regrowing well were seen in this area.

own survey ran through, and beyond, a marked transect of Pearson's. Pearson* ran the second survey somewhat further to the west in an area which he believed to be less well recolonized than the southern corner. The average figures for the two surveys are:

	Mean Cover	Mean No. Colonies	Mean No. Species	Mean Soft
Survey A (P.M.J.W.)	29½%	14	4½	11½%
Survey B (R.P.)	15%	4	3	5%

It is apparent that Pearson's survey had run through a less well-colonized part of the reef, with far fewer colonies and less living coral cover, particularly during the shallower part.

Both surveys began in the deeper region of the slope where patches of sand and rubble began to appear. Very large heads, composed mainly of *Porites*, were common in this part of the fore-slope, some being 10 ft or more in height. Although these large heads had obviously been killed in parts, there were large areas of living *Porites* on the heads. These living areas appeared to be extending and overgrowing the dead areas. The surveys showed a tendency for the amount of coral to increase with decreasing depth, which is typical for normal reefs; but survey B again ran into a poor area in shallowest water. A good assemblage of species was found on the surveys, with branching corals predominating; such species as *Acropora echinata*, *A. exilis*, *A. variabilis*, *A. formosa*, *A. cuneata*, *A. intermedia*, *Seriatopora hystrix*, *Stylophora pistillata*, *S. mordax*, and *Pocillopora damicornis* are very common. Large heads of *Heliopora coerula* occurred in shallower water and many of the latter appeared to have survived the starfish largely intact. In these two surveys 358 colonies were measured, giving an average colony size of about 2¼% square metres.

From my own survey, A, and from a general examination of the southern corner (though this did not include the area of survey B), I concluded that this area, in which *Acanthaster* had been very abundant in 1966, was recolonizing and regrowing very well. In contrast to the 'old glassy patch' the colonies were substantial and growing normally for the region on this type of reef (see final discussion for further comparisons). The remaining dead coral skeletons, which were being cemented into the reef framework, showed growth forms and types of cover essentially similar to the new colonies.

(iv) *SW. Side (Opposite the Cay) Survey*

Two surveys were run from about 18 ft deep up the reef slope in a poorly covered area at the SW. side of the reef, in the vicinity of area B of Barnes's report. This last area contained many sandy areas. There was much movement of sediment with wave surges, and recolonization and growth by reef-building corals were very poor. It was not an area in which corals would be expected to develop the cover found at the southern corner. Even so, recolonization was far less advanced. Soft corals were abundant in the area. Survey summaries are:

	Mean Cover	Mean No. Colonies	Mean No. Species	Mean Soft
Survey A (P.M.J.W.)	4%	2½	2	21%
Survey B (R.P.)	2½%	2	1½	21%

* From this point, Pearson began to use smaller subunits for size measurements than I used. Therefore, to achieve comparability, I have scaled up his *smallest* units (only) to my smallest size size units—1%. This permits comparison of our surveys and also allows them to be considered in relation to my earlier surveys of *undamaged* reefs (using the same methods), which will be discussed here. In the circumstances of underwater surveys, often made in fairly heavy swells, there are limits [illegible] of the smallest measurements

Feather Reef

Feather Reef, some 20 miles off Innisfail, was surveyed at the northern and southern ends ('horns'). The corals had been badly destroyed by starfish in both situations—Pearson had found 267 and 776 starfish per 20 minute survey in October 1966. None were found in August 1969, nor during the present survey, but the approximate date at which starfish left the reef is not known. The starfish had killed almost all of the hard corals in the areas surveyed.

The surveys ran from about 25 ft deep up to the reef flat at the northern end, and from about 15 ft deep (from a sandy fore-slope) on to the flat at the south end. Both showed little living coral cover, recolonization being worst at the southern end where there were considerable sandy patches. The northern horn of the reef was notable for the numbers of soft corals growing on the fore-slope from about 10 ft to 18 ft deep. The survey summaries are:

	Mean Cover	Mean No. Colonies	Mean No. Species	Mean Soft
North end				
Survey A (P.M.J.W.)	6%	4	3	15%
Survey B (R.P.)	6%	4	3½	27%
South end				
Survey A (P.M.J.W.)	3½%	1½	1½	8½%
Survey B (R.P.)	3½%	3	2½	1%

Despite the poor development of hard corals found on Feather Reef during the surveys, the well-washed, clean, coralline rock found particularly on the slopes of the northern horn of the reef suggested that there is now a good substrate for the permanent settlement of new colonies, very like the recolonized northern side of Heron Reef. It may well be worth resurveying this area. At the southern horn sediment movement is likely to make recolonization a more protracted process.

At the southern end of the reef several large *Porites* heads 10 ft and more in diameter had been partially killed, but much of the coral on the heads was living and appeared to be overgrowing the dead areas again, as had been found at Green Island.

Conclusions

The hard corals have recolonized areas of Heron Reef which were entirely denuded of living coral by a cyclone early in 1967. In the ensuing 3½ years recolonization and growth have been good and are continuing. The conditions on the northern slope of Heron Reef are considered to be good for larval settlement because the rock surfaces are clean and well washed, with little sediment. Individual plants of seaweed are common on the slope, but there is no overall cover or mat of algae, as there was for many months after the cyclone. The rock is covered in large part by a pink cementum of coralline algae.

Without another storm, the present conditions for recolonization are unlikely to change. This, coupled with the known growth rates of the hard corals, suggests that the slope will have largely recovered, with a good coverage of well-grown corals, ten years after the cyclone. Personal observation before the 1967 cyclone confirmed that the reef slope was colonized by luxuriant coral growth. The pre-cyclone coral development had probably taken place in the twenty-year period after an earlier cyclone had passed the reef causing about the same amount of damage to the sand cay as in 1967.

The history of the starfish infestation at Green Island has been documented, and from Pearson's surveys the numbers of *Acanthaster* had declined markedly by January 1967 and have not increased since that time. The four widely separated areas of Green Island Reef surveyed showed very different degrees of recovery. The richest area, at the southern corner of the reef, compared with Heron Reef in terms of living coral cover and in numbers of living colonies. On the average, colonies were a little

The recolonization of the back-reef area on the north side of Green Island was not as extensive, in terms of living coral cover, as at the southern corner. However, it must still be considered to be good, taking into account that in the back-reef environment, with much coral standing openly above a partly sandy substrate, the corals would be expected normally to be less densely developed. The average colony size in the northern area was also larger—3% square metre. It is noted, however, that Pearson was not convinced that the majority of corals, other than *Porites*, were new colonies, although *Acanthaster* had been abundant in the area. Soft corals were common but occupied only 8% of the area on average, and are normal in such back-reef environments.

Recolonization had not gone well in the other two areas examined at Green Island—the SW. side and area (ii). In both areas the waters were turbid and there was sediment movement over the ground with wave surge. Both factors would provide poor environments for the settlement and subsequent growth of young colonies. At area (ii) (the 'old glassy patch') very turbid waters reduced incident light and, probably more significantly, coated dead coral surfaces with fine silts. Many corals had begun to regrow, or new colonies had been established, but often on insubstantial old skeletons, which would have been broken down in a more exposed position. In area (iv) at the SW. side, the rapid back-and-forth movement of coarser sands with the wave surge was probably more significant than the generally turbid waters.

At Feather Reef, it was not known when *Acanthaster* had left the reef, but recolonization by living coral had not proceeded far in the two parts of the reef which were examined. At the southern horn the large areas of sand and the low slope of the fore-reef were somewhat analogous to the SW. side of Green Island and sand movement would probably contribute to a slow rate of recolonization. However, at the northern end of the reef, the fore-slope was well-washed clean rock, and despite the extensive development of soft corals at depths of about 10 to 18 ft, it would be expected that good settlement and regrowth of hard corals would now occur on this clean substrate. The recolonization of Heron Reef went ahead well after the rock surface had been cleared in a similar manner.

Comparison of Green Island with Undamaged Reefs

It is of interest to compare the development and specific composition of corals on the recolonized southern corner of Green Island with similar situations in other northern inner patch reefs which have not been damaged by *Acanthaster*. I have data for two reefs, Low Island and Nymph Island, collected in precisely the same manner by using underwater quadrat surveys. The survey sections taken ran from about 25 ft deep into shallow water, as at Green Island, and were both made at southern corners of the respective reefs. The summarized results are in good agreement. Both reefs showed similar average numbers of colonies to Green Island, but the colonies were larger being 4% square metre in each case (compared with about 2% square metre at Green Island), and so the overall living coral cover was also greater. These comparisons of mean values are:

	Area Coral	No. Colonies	No. Species	No. Quadrats
Green Island	29½%	14	4½	25
Low Island	52%	13	6	12
Nymph Island	44%	10½	7	20

The species assemblages on the two undamaged reefs also bore resemblances to that at Green Island. They suggest that good recovery was under way at Green Island, at least for the southern corner, within 3½ years of the starfish leaving.

Comparison between Coral Damage by Cyclones and by Starfish, in relation to Recolonization

It is fairly clear that damage by starfish to the living corals of a reef may be more severe than that caused by a cyclone in that (i) a storm will not usually damage all sides of a reef; there is frequently a lee-side, or at least sheltered embayment; (ii) the reef flat is protected from the worst of living coral may remain untouched and there are suggestions that the starfish avoid the shallows of the reef flat in some situations. Thus, the mere presence of a heavy infestation need not mean that all the coral on a reef is doomed.

For recolonization by hard corals, the present results suggest that clear, clean rock surfaces and clear water will achieve best settlement rates. Conversely, coarse and fine sediments frequently disturbed by waves, and turbid waters, will not provide good conditions. This is in agreement with investigations elsewhere. Where cyclone damage is severe, the coral rock is stripped bare of colonies over large areas and, although there is a cycle of algae growth and sediment deposition, this phase is likely to pass and leave clean rock surfaces providing a substantial substrate. Damage by *Acanthaster*, like that due to freshwater flooding or temporary large-scale sediment movement, kills the coral but leaves the skeleton in position. The standing skeletons tend to trap sediment and reduce the rates of circulation of water across the reef. They will erode and crumble to rubble, which will eventually be cemented into the rock of the reef. This will take a varying time depending on several factors such as the situation on a particular reef, the location of the reef itself, and the degree of exposure to wave action. It seems quite likely that a 'good storm' might serve to speed up such a process, particularly in the normally sheltered situations of the reef (e.g. the 'old glassy patch' at Green Island). Nevertheless, there appears to be no evidence to suggest that the reefs will not recover fully with time, though recovery is likely to take longer in some situations than in others. The recovery in the best areas seen at Green Island is remarkable, and it would have been exciting to be able to carry out further surveys to assess recolonization more completely.

It was most interesting to find that the very large pillars and heads of *Porites* in particular, which are undoubtedly very old, appeared to be regrowing over many parts. It appeared that these heads might well recover completely within a few years.

Acknowledgments

I am most grateful to the Committee for their support in making these surveys. It is a pleasure to express my thanks to Dr. J. M. Harvey, Director-General, Department of Primary Industries, Queensland, and to members of the Fisheries Section of that Department, for their ready and willing assistance, and not least to my capable, hard-working, and jovial companions R. Pearson and J. Bloomfield.

APPENDIX F

Pesticide Accumulation in Great Barrier Reef Food Chains

By D. J. Tranter, CSIRO

Introduction

The Great Barrier Reef 'lagoon' is a saucer of coastal water, bordered on its outer edge by the network of coral reefs known collectively as the Great Barrier Reef, and on its inner edge by the mainland coastline. Into this shallow basin monsoonal rivers empty, carrying silt at floodtime from farms and pastures in the hinterland. It is likely that nutrients and undegraded pesticides carried by rivers into the sea would be taken up and incorporated into neritic food chains.

Because corals, clams, and other reef organisms contain within their tissues large populations of algae (zooxanthellae) which are adapted for removing small traces of nutrients from water flowing past, it is likely that any pesticides that reach the reefs would be incorporated and concentrated in the tissues of the coral with which the algae have a symbiotic relationship. Further, because corals are relatively long-lived, such concentrations, if any, will tend to be contained and localized there for long periods of time.

The starfish *Acanthaster planci* feeds almost exclusively on corals and would ingest whatever pesticides are contained within the tissues of the coral, concentrating the chlorinated hydrocarbons, as is usual, in fatty tissues such as gonads. The report that concentrations of PCBs had been recorded by McCloskey in plague *Acanthaster* from Guam consequently assumed a special interest. It seemed clear that the question of pesticide accumulation in Great Barrier Reef food chains would have to be looked at, and that some pilot survey should be done to estimate the priority that should be given to such an investigation.

With this in mind, samples were taken from reefs in the Townsville area in July 1970 for pesticide analysis. Methods were available only for determination of chlorinated hydrocarbons, but these seemed to present the greatest pollution hazard in view of their use in the tobacco, sugar, and pastoral industries. The material sampled consisted of *Acanthaster* gonads, gonads from the starfish *Linckia* which does not usually feed on corals, the mantle edge of the clam *Tridacna* in which large concentrations of zooxanthellae are located, and some corals of the genus *Fungia*. The samples were taken from reefs in The Slashers, John Brewer Reef, and Lodestone Reef east of Townsville. Samples were taken both on the outer crest and on the reef flat. Adult starfish were selected for sampling; the gonads were generally well formed but not yet ripe. There was sufficient material in a single *Acanthaster* for a sample, but the gonads of several *Linckia* had to be pooled.

Dissection was done with a minimum of contamination, and the samples were wrapped in aluminium foil and stored on ice in an insulated box. The analysis was done in the biochemistry laboratories of the Department of Primary Industries under the supervision of Mr. W. McCray. The report of the results of the analyses is given below.

The results show that the amounts of the pesticides analysed were very low in the tissues sampled. Though the samples were small, it seemed probable, from this pilot survey, that the reefs from which the samples were taken were not greatly polluted by those pesticides. It would seem desirable for a more thorough survey to be made including reefs closer to the mouths of rivers draining areas where large concentrations of pesticide are used in agriculture. A study on the effect of low pesticide concentrations on the larvae of *Acanthaster* would also be of great value.

Results (communicated by W. McCray, Department of Primary Industries, Queensland)

Samples were collected as follows:

Lodestone Reef.—*Acanthaster* gonad (5), *Linckia* gonad (3), *Tridacna* gonad (2), *Tridacna* mantle-edge (2), *Fungia* (3).

The samples were examined by electron capture gas liquid chromatography. The level of response indicated chlorinated hydrocarbon contamination of a very low order which rarely exceeded the level of significance related to sample size.

Some chlorinated hydrocarbon pesticides were identifiable and in samples where the chromatographic pattern was complex and the sample size permitted partition chromatography was used to separate insecticides from polychlorinated biphenyls.

All 16 samples of *Acanthaster* and all 6 *Linckia* samples were examined. One sample of *Tridacna* gonad and one of mantle-edge from The Slashers Reef were examined.

The results of analyses expressed as parts per billion (nanogrammes per gramme) are as follows:

Insecticides (*Acanthaster* Gonads).—

Reef	DDT	DDE	BHC	Dieldrin	Endrin
The Slashers	5	5	—	19	—
	—	—	—	—	8
	—	—	1	—	—
	—	1	—	—	—
	7	7	—	—	—
	—	10	1	—	5
John Brewer	—	14	—	—	—
	—	—	—	15	—
	12	24	—	—	—
	6	34	—	—	—
Lodestone	5	—	—	—	—
	—	—	—	—	—
	—	6	—	—	—
	—	—	—	—	—
	—	—	—	—	—
	—	—	—	—	—

Insecticides (*Linckia* and *Tridacna* Gonads).—No levels above significance (1 ppb) were detected in the six *Linckia* or the two *Tridacna* samples.

Polychlorinated Biphenyls (All Species).—No levels greater than 10 ppb were detected in the samples differentially examined for insecticides and PCBs. (A sensitivity similar to that of DDT in detection was assumed for purposes of estimation in the absence of reference material.)

Unknown Compounds.—An unknown compound occurred in a few samples but this could not be classified or quantified in the time available.

The apparent increase in insecticide levels in samples from John Brewer Reef is not significant at the levels detected and is part of a general picture of extremely low pesticide burdens in these species. In *Acanthaster*, of 80 pesticide/sample combinations only 19 reached a detectable pesticide level in relation to sample size. In all other species/contaminant combinations, excepting a few occurrences of PCBs, levels were not in excess of 1 ppb.

It is not conceivable that these levels found in species from infested reefs would prove greater than those from other reefs given similar sample size and detection techniques.

APPENDIX G

Echinoderm Debris from Great Barrier Reef Sediment—Distribution and Age

By Associate Professor W. G. H. Maxwell, University of Sydney

During the period 1963–67, a marine geological survey of the Great Barrier Reef Province resulted in the collection of several thousands of sediment samples over an area extending from shore-line to shelf-edge and from Bustard Head to Torres Strait. Analysis of this material revealed that the echinoderm fraction increased from an insignificant amount in the southern samples to quite large values in those from the northern region. Because of their possible importance to research on *Acanthaster*, a random selection of 643 samples was made from the total number from the shelf and these were re-analysed specifically for echinoderm content.

Table 1.—Echinoderm Detrital Variation

Area	No. of Samples	Echinoderm Percentage Mean	Maximum
Southern region			
1. Capricorn–Bunker Group	147	1·6	8·3
2. Swains complex	52	2·3	8·4
3. West shelf: Fitzroy–Mackay	36	2·5	9·0
4. Pompey complex	27	3·9	10·6
Total	262	2·1	10·6
Central region			
5. Townsville inner shelf	19	2·5	6·4
6. Palm Island Group	13	3·2	6·6
7. Inner reefs, Townsville	20	3·9	10·8
8. Cairns–Ingham shelf and reefs	52	2·6	20·0
9. Port Douglas–Cooktown	29	4·4	27·8
Total	133	3·1	27·8
Northern region			
10. Cooktown–Princess Charlotte Bay	112	5·4	46·6
11. Princess Charlotte Bay–Torres Strait	136	6·4	32·4
Total	248	6·0	46·6
Total for Great Barrier Reef Province	643	3·8	46·6

Further studies were undertaken on the microskeletal structure of different common groups of the Echinodermata in an attempt to find diagnostic criteria for distinguishing these groups and, in particular, *Acanthaster*. Three main skeletal-structural groups were recognized, viz. (i) forms with dense moderately porous skeletal material. Echinoids, the majority of Asteroids, (ii) forms with coarse

Consequently in referring skeletal detritus to an *Acanthaster* source, the accuracy of identification is reduced because of similarity of Ophiuroid microstructure. Where there is a marked increase in the echinoderm fraction one can only infer that one or other of the three groups has been responsible. Reliable assessment of *Acanthaster* alone cannot be made.

In addition to the geographic variation in the composition of sediment, the age of sediment from various areas was also determined by radiocarbon methods. Again the primary objective of this project was not concerned with the *Acanthaster* problem, but because of its possible relevance to previous infestations in the reef province, several samples containing high echinoderm (group ii) fractions were subsequently submitted for dating.

Table 2

Area*	Sample	Date (Years B.P.)	Ech. %	Regional Ech. %†	Depth (fm)	Location
Southern region						
1	194	4950 ± 70	—	1·6(6)	20	S. of Masthead
2‡	3043	390 ± 80	—	3·1(8)	24	Inter-reef, NE. Swains
	3082	630 ± 90	—	0(4)	0	Beach rock, Twin Cay, Swains
	3097	1110 ± 80	—	0(4)	0	Beach rock, Twin Cay
	8000	5680 ± 260	—	2·5(36)	0	15-ft core, 25 miles W. of Swains
3	3268	2970 ± 90	—	2·8(2)	32	4 miles NE. Pine Islet
	3271	0 ± 70	—	3·0(2)	39	W. of Lakatoi Reef
	3277	2150 ± 90	—	4·2(1)	22	S. of Pine Peak I.
	3321	1700 ± 90	—	—	17	W. of Percy I.
Central region						
7§	4343	830 ± 80	2·6	4·1(3)	23	W. of Keeper Reef
Northern region						
10	5595X	530 ± 80	—	—	0	Beach rock, Nymph Reef
10‡	5690	250 ± 80	4·2	—	0	Beach rock, Turtle Reef
11	5877	680 ± 80	—	—	0	Beach rock, Magra Reef
12	5880	770 ± 90	—	—	0	Coral head, Magra Reef
13	5949	2810 ± 90	—	0·6(1)	0	Old reef surface, Hawkesbury I.
14	5961	5120 ± 120	—	—	0	Old reef surface, Prince of Wales I.
15§	5993	1500 ± 100	35·4	16·9(3)	12	Adjacent to Piper Reef

* Area numbers tabulated in column 1 correspond to same numbers in Table 1.

† Regional echinoderm % is based on the mean % of samples taken from the surrounding area. The numbers in brackets refer to the number of samples on which the mean is based.

‡ Previous age determinations on echinoderm-rich material.

§ Sample selected specifically for echinoderm dating; process still continuing and age range given represents maximum and minimum limits for total sediment; age determination of extracted echinoderm detritus is still in progress.

Distributing of Echinoderm Detritus

The concentration of echinoderm material in sediment from 643 samples taken from south to north through the Great Barrier Reef Province is shown in Table 1. The data are separated into three

Except for minor fluctuation, there is a progressive increase in echinoderm percentage as one proceeds from south to north. There is also a noticeable increase in the southern samples as one proceeds from the reef-less inner shelf to the main reef zone.

Ages of Sediment and Echinoderm Detritus

A modest programme of radiocarbon dating of sediment, beach-rock, and dead reef material was commenced in 1967 with the aim of establishing the sequence of sediment formation on the shelf and of relating this to past sea-level changes. Most of the material used did *not* come from areas of high echinoderm detrital concentrations. However, in 1970, samples from areas of high content, viz. Keeper Reef and Piper Reef in the central and northern regions respectively, were submitted to the Australian National University Radiocarbon Dating Laboratory. Initial results on two sediment samples from localities more than 600 miles apart indicate ages of 830 and 1500 years.

In addition to these two samples, one of beach-rock from Turtle Reef, approximately mid-way between Keeper and Piper Reef, has an echinoderm (group ii) content of 4·2% and an age of 250 ± 80 years. This age was determined by Japanese geochronologists two years before the A.N.U. investigation was commenced.

A fourth sample from an area of moderately high echinoderm detrital content in the north-eastern Swains complex gave a date of 390 ± 80 years.

Thus, on the meagre information available, there is an indication of echinoderm build-up in different parts of the reef province about 300 years ago, 800 years ago, and 1500 years ago.

Determinations on other samples from the Great Barrier Reef Province have been included in Table 2 to illustrate the wide range of age (0–5680 years) for sediment, much of which is free of echinoderm debris.