Giant Clams in Asia and the Pacific

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Giant Clams in Asia and the Pacific

Editors: **J.W. Copland and J.S. Lucas**

Australian Centre for International Agricultural Research
Canberra 1988

Contents

Foreword

Farming giant clams, the huge bivalve shellfish found on Australia's Great Barrier Reef and the tropical reefs of the Indo-Pacific Ocean, could become a significant new industry in Australia and in countries of Southeast Asia and the South Pacific.

Results presented at a workshop at James Cook University in April 1988 indicate that the culture of giant tridacnid clams is both technically and economically viable, with markets for both clam meat, particularly in Taiwan and Japan, and for the shells. The latter are used in a variety of ways, and can be marketed through the well-established shell trade.

This publication brings together the literature and results of most of the world's research on giant clams, most of which was presented at the workshop, and is likely to be a benchmark on the knowledge and potential of giant clams for the restocking of tropical reefs, and farming clams both extensively and intensively, in the Indo-Pacific region.

Throughout much of their geographic range, giant clams have been overexploited, and in some areas of Indonesia, the Philippines, Micronesia and southern Japan some species are now extinct. Because the clams require clean, shallow, warm seawater and plenty of sunlight to survive, they are easy prey for fishermen. The research work reported here will make it possible to restock the areas where the two largest species, *Tridacna gigas* and *Tridacna derasa*, were once plentiful, and help establish a reliable additional source of valuable food protein for people throughout the region.

There are many problems to be overcome before the farming of giant clams becomes an established new industry. The research so far strongly indicates that clam mariculture has considerable potential even at this early stage of development.

ACIAR is pleased to have played a pioneering role in this exciting research, and we believe this publication will serve to stimulate further interest in giant clam mariculture. I would like to thank James Cook University for hosting the workshop, and for the strong support for the Giant Clam Project extended by the Vice-Chancellor Prof. Ray Golding. The workshop was officially opened by Mr Tony A. Burreket, MLA, Townsville.

J.R. McWilliam
Director
Australian Centre for International
Agricultural Research

Summary of Discussion and Recommendations

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i) General

1. The lack of an adequate knowledge base on the biological and socioeconomic aspects of tridacnid clams, especially *Tridacna gigas, T. derasa* and *T. maxima*, was identified as a major constraint to the management, conservation, development and protection of current and future clam resources.
2. There is a need to develop adequate communications between research and development agencies to prevent duplication of effort and to establish a data base for the restocking of reefs, conservation and mariculture of giant clams.
3. It was recommended that current knowledge on the culture and management of giant clams be made available in a manual for countries in the South Pacific and Southeast Asia who are interested in the mariculture of giant clams.

ii) Socioeconomic Aspects of Clam Culture

1. There is a need to identify the potential export market for the various products of clams to the developed countries of the Pacific Basin.
2. A better understanding is required of the reef ownership patterns, and the cultural and economic implications of clam culture need to be assessed on a country-specific basis prior to restocking reefs and the establishment of clam mariculture operations.
3. The shellfish consumption patterns and internal market characteristics of South Pacific countries need to be assessed.
4. The production costs, postharvest, transport and packaging requirements for low-cost and capital-intensive production systems need to be evaluated and export markets determined.
5. The economic benefits, if any, of polyculture need to be determined.
6. The likely social and income distributional impacts and gender roles of low-cost giant clam production systems in the South Pacific need to be evaluated.
7. Research is required to determine the degree of substitution of clam meat with low-cost products such as scallops.

iii) Biology of Wildstock

1. It was strongly recommended that the existing genetic diversity of the tridacnid species be established throughout their natural distribution, with particular reference to the following:
   (a) Genetic diversity within discrete tridacnid populations;
   (b) Relationship between growth rate, survival and desired production characteristics in areas which have a suitable number of tridacnid species.

2. A study should be made of the strains of zooxanthellae that form a symbiotic relationship with tridacnid clams, to determine the most efficient strain for survival and growth of all stages of the giant clams.
3. It was recommended that a gene bank of tridacnid species be established, particularly those of likely importance for restocking reefs and mariculture.
4. Identification of the most suitable broodstock based on the best genetic fit was considered to be a high priority for both restocking and mariculture of giant clams.
5. The identification of the genetic/environmental interactions of *T. gigas* was considered a high priority for the efficient management of wild and cultured clams.
6. Understanding the short- and long-term impact of mixing tridacnid gene pools from different populations was a high priority for further research.
7. The increased productivity of *T. gigas* by genetic selection needs to be evaluated, and suitable criteria need to be established for selection of desired characteristics.

iv) Reproduction and Early Stage Survival

1. A high research priority is the identification of the environmental and biological factors that induce spawning of giant clams.
2. Research is needed to develop techniques to extend the length of the spawning season without loss of gamete viability.
3. It was strongly recommended that research be undertaken to identify the biological and environmental factors influencing the survival of the early larval stage of development of tridacnid clams, with particular emphasis on:
   - the identification of the optimum requirements for settlement and survival of the larvae;
   - the establishment of the importance of various substrates such as colour, shape, and texture in larval settlement and survival; and
   - the development of improved, low-cost hatchery designs and techniques to improve larval survival.

v) Nutrition of Giant Clams

1. Determining the nutritional requirements of the larval stage of giant clams is a high research priority, with emphasis on the following:
   - identification of environmental factors that influence the nutritional status of larvae up to post-settlement stage;
   - evaluation of the benefits of added nutrients for the larvae;
   - clarification of the factors that accelerate or impede the development of a successful symbiosis between juvenile clams and the zooxanthellae.
2. It was recommended that techniques be developed to manipulate and replace zooxanthellae during the various stages in the life cycle of the clams, given the pivotal nutritional role of zooxanthellae.
3. It was recommended that the environmental and biological requirements for zooxanthellae be determined.
4. It is important to develop microcapsule techniques to replace the need for algal feeding of the clam larvae.

vi) Mariculture of Giant Clams

1. It was agreed that there is an urgent need to determine the most suitable environmental parameters for the culture of juvenile and adult giant clams. The parameters should be measured in such a manner that they can be reproduced elsewhere. Emphasis should be placed on water temperature, water exchange volume and rate, sunlight intensity and duration, depth of clams and other relevant oceanographic factors for nursery and grow-out sites. This will help establish the necessary site criteria for the various species of giant clams.
2. It is important to develop low-cost mariculture techniques for restocking of reefs, subsistence and artisanal mariculture.
3. Research should be carried out to develop or adapt existing growth models and techniques to monitor growth of giant clams.
4. Research is needed to identify the optimal environmental and management factors that affect the quantity and quality of clam meat and shells.
5. It was recommended that the physical markers of 'slow growers' be identified and the impact of various culling rates be evaluated in relation to the total biomass.
6. The potential of clam polyculture with seaweed and other marine organisms needs to be evaluated in biological and economic terms.

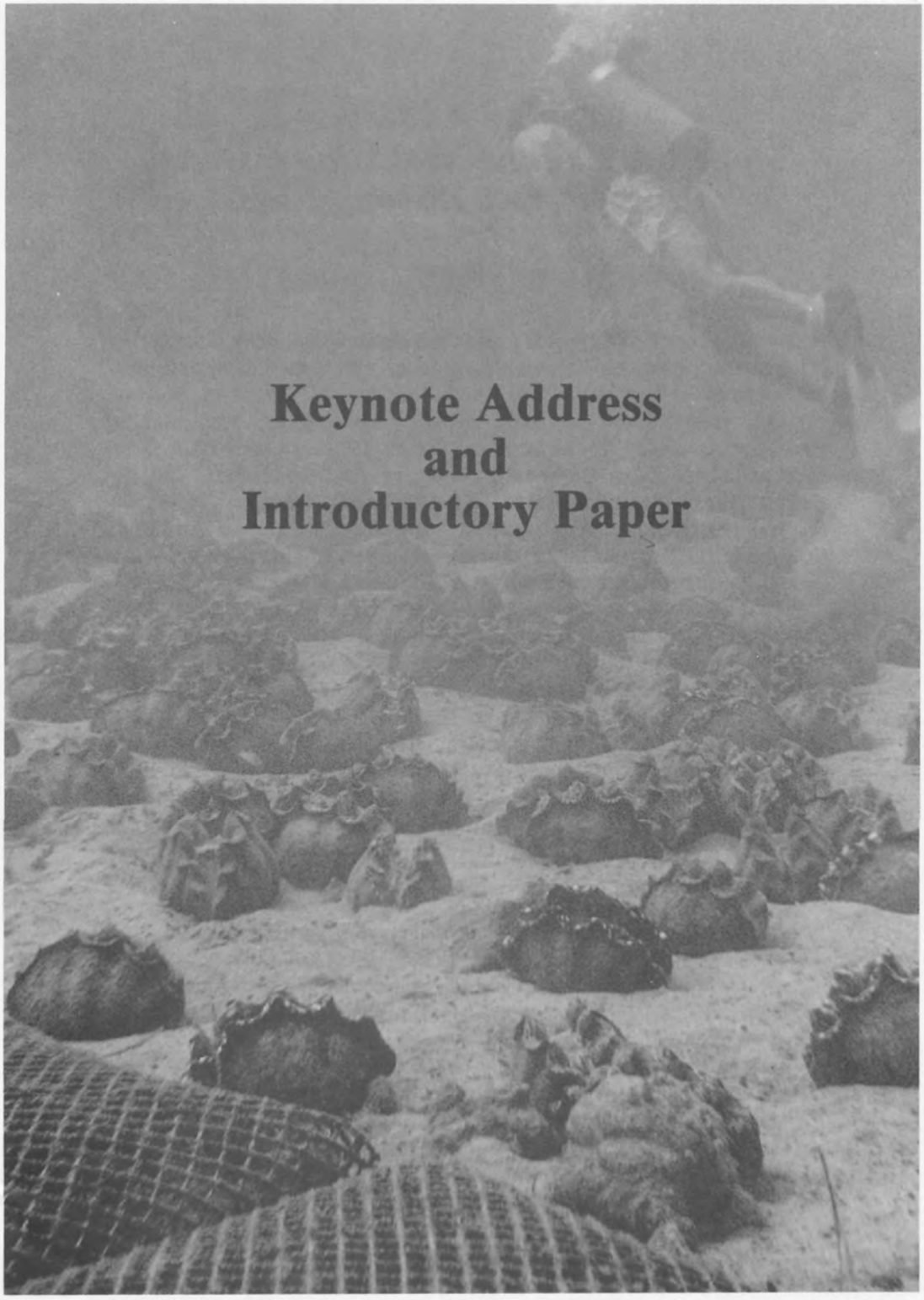
vii) Restocking and Conservation of Reefs with Clams

1. A detailed study of the existing stocks of giant clams is necessary in some countries to determine availability of broodstock and identification of the most suitable species for culture and restocking of reefs.
2. Identification of tropical reefs suitable for restocking is a high priority. It was recommended that remote sensing data be examined as a method of identifying suitable reefs.
3. Research on low-cost techniques to restock and maintain suitable reefs needs to be developed.
4. It was recommended that countries that have significant clam resources consider procedures to maintain and enhance their existing stocks.
5. It was also recommended that research be carried out on the environmental impact of clam farms on tropical reefs.

viii) Disease and Predator Research

1. A high priority research topic is the identification of existing pathogens of giant clams and their zooxanthellae, with particular emphasis on infectious agents.
2. Research activities should be conducted into the normal microbial flora of clams to allow differentiation between pathogenic and nonpathogenic forms.
3. A multidisciplinary investigation is required into monitoring of stress-inducing management processes to determine the short- and long-term impact on growth.
4. It is necessary to successfully diagnose the noninfectious and infectious disease processes and their aetiology; research is necessary to establish descriptions of the normal tissues and their response to damage.

5. It is recommended that emphasis be placed on the identification of infectious pathogenic agents that may be transported by the movement of clams from one region or country to another. This has particular relevance to the quarantine precautions that need to be undertaken for such translocations of clams.
6. The identification and control of the predators of clams during the various phases of culture, with particular reference to the nursery stage, were identified as important areas for further study.
7. It was strongly recommended that a regional centre be established for the collection, diagnosis and dissemination of information on clam diseases and quarantine procedures.



Keynote Address and Introductory Paper

Keynote Address: Scope for National and International Research and Development

J.T. Baker*

IT is a unique opportunity to sit among the pioneers in a field of study!

Certainly one can look at the bibliographies on the giant clams and find references as far back as de Blainville in 1825, but the current emphasis on farming giant clams has built on the science-based technological developments of the 1970s and revealed the late 1970s and early 1980s as the focal period for the principal early studies on clam mariculture. One can also go back to books which we in Australia treasure for their pioneering role in popularising marine research. In the book by Dakin called 'Australian Seashores,' clams do not even receive a single mention. One must admit that Dakin's book had a heavy emphasis on New South Wales. Perhaps there is a place for a newer book on 'Australia's Intertidal Regions.'

Australia became involved in this mariculture development because a new organisation called the Australian Centre for International Agricultural Research appreciated from its first days that farming the sea was at least as important as farming the land.

ACIAR built on the findings of the International Center for Living Aquatic Resources Management (ICLARM) and the Micronesian Mariculture Demonstration Center (MMDC) and entered the field by supporting a study, coordinated through James Cook University, in the development of a series of bilateral agreements with the Philippines, Fiji and Papua New Guinea.

This series of agreements depended on the interest and relevant — but not at that time direct — expertise of staff at James Cook University to allow Australia's entry into this new field of research which could be seen as having benefit to science, to the community, to entrepreneurs and to restoration of ecological balance, by reseeding of heavily exploited near-shore and reef areas.

One is tempted to name the obvious pioneers among you, at this time. Certainly they merit that recognition, but I will resist the temptation because the exploration and development are too current for me to be sure that I will not inadvertently omit a name. I would not wish to do an injustice to those younger pioneers who may, for the moment, be not clearly obvious because of the shadows in which they do, temporarily, stand.

* Director, Australian Institute of Marine Science, Townsville, Qld, Australia.

The efforts of ACIAR, ICLARM, MMDC and of several individual governments have resulted in parallel pioneering in many countries, the vast majority of which are represented here today.

In these next few days we will work among the pioneers and we face several distinct challenges:

- to share our scientific knowledge;
- to forge the bonds of trust and friendship, facilitating ongoing open exchange of information and collaboration, and thus overcome the frustrations of isolation in our practical efforts when we return to our home countries;
- to identify the place at which we stand, relative to the objective of commercial development of clam products;
- to be tolerant in developing the art of communication among scientists, policymakers, commercial developers and conservationists;
- to clearly identify the environmental and health problems which we must address, if we are to develop an international trade;
- to consider the most appropriate ways to satisfy our ongoing needs for training, information and supply of stock and 'seed,' in such a vast geographic region;
- to show maturity in all aspects so that at the end of this week we identify you not only as the pioneers of a new farming industry, but also as the statesmen of an essential, internationally important industry.

It is not our place to hide problems or to be hesitant in revealing a lack of understanding. Rather it is our duty to expose the weaknesses as well as the strengths of our understanding as we move to consolidate the foundations of a new, but potentially long-lived, industry.

One way to focus your attention as I develop my theme is to share with you my impressions of the steps to the development of this farming industry, based on the obvious products we anticipate (Fig. 1). You may well prefer alternative representations. Mine is very much a projection of a possible way to develop.

When one compares this sequence with the workshop topics that have been planned, we are still very much concerned with the scientific and technological problems involving broodstock, hatchery and nursery features, seed production and transport, stock assessment, predators, parasites and diseases.

By your efforts you have developed a better, but in no ways complete, understanding of: (i) the reproductive biology of giant clams, with particular reference to the regularity of their spawning cycles and the different methods for, and results of, induction of spawning; (ii) optimal conditions for larval survival and development; (iii) development of juveniles; (iv) understanding of predator-prey relationships; and (v) growth rates under different conditions.

Relevance of the results to different institutions has varied because of the differing types of institutions. For the universities, the ACIAR support has led to a much more rapid development of staff expertise and involvement than could otherwise have been practicable and, in the vast majority of cases, has led to improved communication between the university and the

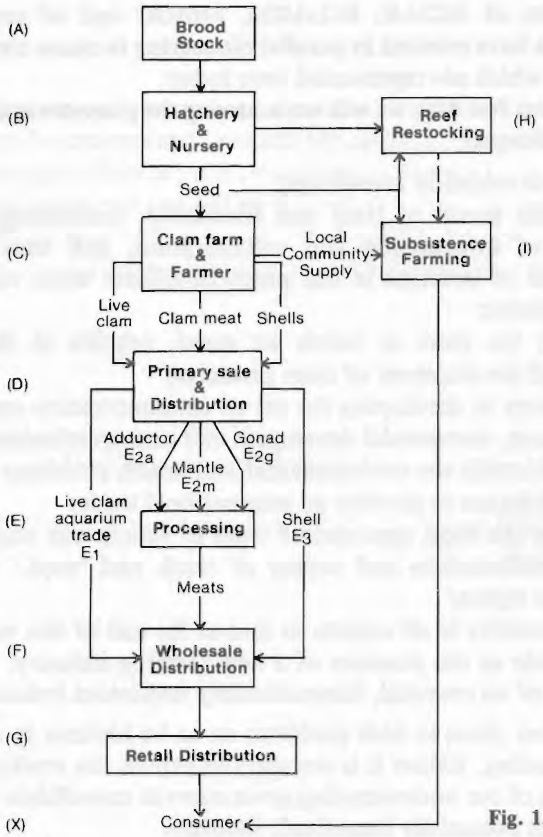


Fig. 1.

community. For the Fiji Fisheries Department, project results have stimulated the development of soundly based management strategies and encouraged the development of a field quarantine station which can be extended as a hatchery and possible 'grow-out' facility.

The spirit of scientific collaboration has been generally well developed among the representatives of the institutions. It has not been perfect and the next stage of support will require a committed effort to ensure stronger collaboration, not only across international boundaries, but also within countries, among universities, government agencies, community groups and, hopefully, commercial developers. Scientific collaboration, in the free exchange of information as soon as it becomes available, does not appear to have always been effected in the first stage of this project. Our review of the project suggests mechanisms to improve collaboration and information exchange.

Today, I await with great interest the opportunity to listen to the country presentations from Kiribati, Tonga, the Cook Islands, Solomon Islands and the Federated States of Micronesia to compare their priorities with those of the Philippines, Fiji, Papua New Guinea and Australia.

The priorities may well differ greatly but I do suspect that there will be interest emerging on the status of 'need' to move to an ability to restock reefs, to develop subsistence farming, and to define the essential features of

a successful clam farm. From these will emerge the demand to know what are the 'saleable' products, how should the products be processed and packed and where can they be sold?

In parallel, there will be the need to understand the challenges and impacts of high-density clam farming, the country requirements of export and import of live animals, the conservation issues, and the legal requirements associated with each country's laws as they affect the suitable areas for farms.

The final session of the workshop receives reports from discussion sessions, and will also consider and develop specific recommendations on future research priorities.

This is where the challenge of statesmanship clearly emerges and there is a need to carefully consider the differing requirements of each country and how such requirements may best be met. From these recommendations, ACIAR will distill the essential focal areas for a new program, perhaps not by itself this time, but in collaboration with industrial or other government partners.

There is no doubt in my mind that the recommendations must reveal a transition from a principal science and technology support to consideration of socioeconomic factors, and to consideration of the applications of the research to date for conservation, for community and for commercial benefit.

ACIAR, like all Australian Government agencies, must be encouraged by you to follow these at first apparently diverging paths, seeking industry collaboration and financial involvement in the commercial areas, and government support in the community and conservation areas.

There is a need for very clear policies to be developed in the different countries if profit-making clam mariculture is to be developed in parallel with practices of subsistence farming and restocking reefs. 'Regional planning' of marine areas will probably be a natural consequence of these different types of objectives. The need for such regional planning should be a feature of further ACIAR support of giant clam research.

From our experience we believe that there is scope for consideration of a number of subregional centres for several different functions, shown in Table 1. Perhaps you would have a different perspective and I would respect your advice. You are the people who can best evaluate your own country and regional requirements.

From the technical viewpoint it is clear that clam mariculture can be viable on a continuing and very long-term basis.

If one compares the clam-farming industry with the early days of wheat, sugar cane or sheep farming, your scientific knowledge on clams is greater than was the knowledge on any of those other farm products when they were first introduced. We must expect the commercial pressure and we must establish long-term interactive associations with the industries that develop from clam mariculture.

The rate of acceptance of the technology of clam mariculture will be determined more by its appropriateness to local social, cultural and economic conditions than to technical and technological factors. Understanding of the different local cultures and expectations is essential.

TABLE 1. Possible subregional 'centres' for development of giant clam mariculture.

Country	Short-term (3–8 years)	Long-term (> 8 years)
Philippines	Own-country needs	Asia and World markets
Palau	Philippines Micronesia USA aquarium trade Specialty shell trade International training function	As for short-term
Solomon Islands	Own-country needs	Add Vanuatu Kiribati
New Caledonia	French Territories	South Pacific
Fiji	Own country and Tuvalu, Tokelau, Samoa, Tonga, Cook Islands	As for short-term — seek export markets
Australia[a]	Own country Plus research of general regional value and training function	As for short-term
Papua New Guinea[a]	Own country needs	Seek export markets

[a] Likely commercial venture funding.

Therefore it is equally essential that a strong and more extensive local involvement in the project development be ensured, to build indigenous ongoing research competence.

It is now the stage of development in which we must ensure the closest practicable association between the technical experts and policymakers in each of the countries.

In this workshop we must all further develop the awareness and skills that will make us more efficient communicators to our decision-makers. In our review team experience at the government level in virtually all countries involved, there was an evident general apprehension about the prospects of mariculture and on the wide applicability of clam mariculture in particular. There remains a general and erroneous belief that clam growth is so slow that the species will be continually susceptible to human overpredation and unsuccessful as a commercially farmed species. You must correct such impressions — not by science but by communication.

A high priority must be placed on ways to ensure personal involvement of decision-makers in awareness of the advances made in clam mariculture. Once clam farms overcome the first 5 years or so of limited financial return, the crop is continuous, and the analogy may well be drawn to coconut farming which is well known to most Pacific countries.

Now I leave you to your own thoughts during these important days. You will learn a great deal. You will also have the opportunity to help each other in that learning. As pioneers, be not afraid to ask your questions freely and to seek a clearer understanding of the differing challenges and opportunities in this emerging truly biotechnological industry. As statesmen of the emerging industry be considerate of the differing needs of your fellows, and plan for the long-term security of the clam species involved, and of the industries which will be based on them.

I wish you well in your deliberations.

Giant Clams: Description, Distribution and Life History

John S. Lucas*

Abstract

The seven species of giant clams are briefly described and a key provided for their identification. Giant clams are unique among bivalved molluscs in having symbiotic algae in their mantle tissues. Being dependent on this symbiosis for at least some of their nutrition has profound effects on their morphology and ecology. The larval development of giant clams is quite typical of bivalved molluscs, but soon after metamorphosis the symbiosis is established and the clams are thereafter phototrophic. Growth is rapid in the larger species. Giant clams have been overexploited in recent decades by local and foreign fishermen. Recognition of declining stocks of giant clams and of their potential for mariculture has given recent impetus for research.

THERE is a dramatic difference in perception of giant clams between Western people and the peoples of the Pacific Islands and Southeast Asia. Pacific islanders and some Southeast Asians eat giant clams as one of many foods gleaned from coral reefs. Chinese regard the adductor muscle tissue from giant clams as a highly prized delicacy with aphrodisiac properties. However, westerners' perceptions of giant clams are from lurid adventure stories and films of the hazards of coral reefs. For example, one account of giant clams in a serious natural history magazine described how 'It is *not unusual* for a diver to be caught in the jaws of one of these giant clams, which clamp shut with the *suddenness* and strength of a bear trap' (my italics) (Cobb 1939). These stories have led to giant clams being called 'killer clams,' a title which is totally inappropriate for these benign, phototrophic animals.

Partly because of this strange perception of giant clams, but mainly because of their occurrence in tropical waters far from the main centres of marine science, there has been surprisingly little research on giant clams until quite recently. The great British marine biologist, Sir Maurice Yonge, was one of the few who took a long-term interest in giant clams (e.g. Yonge 1936, 1980).

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Species

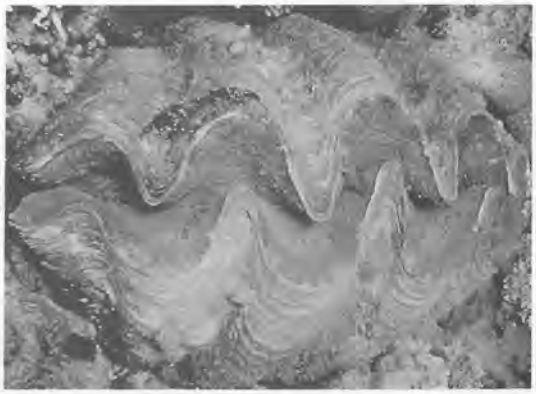
Rosewater (1965) revised the confused taxonomy of the giant clam family, Tridacnidae, recognising six living species in two genera, *Tridacna* Bruguiere and *Hippopus* Lamarck. He subsequently described another *Hippopus* species to bring the total to seven species (Rosewater 1982). Rosewater's taxonomy of the giant clams has been universally accepted; however, it is possible that there are taxa as yet unrecognised (see Lewis and Ledua, This Monograph).

Giant clam species range in size from adult shell lengths about 15 cm to greater than 1 m. Only one species, *T. gigas*, usually grows to more than 50 cm shell length and is truly gigantic. It is the largest bivalved mollusc that has ever existed.

The seven living species of giant clams are described on the following pages (see Govan, This Monograph, for the names of the species in various Pacific languages).

Tridacna gigas **(Giant Clam)**

Shells sometimes grow to over 1 m long and are very thick near the base. A single shell may weigh up to 200 kg. This species may be readily identified by its size and also by the elongate, triangular projections of the upper margins of the shells. The mantle is brown and has numerous small blue-green circles, particularly along the lateral edges. This species is nearly extinct or recently extinct over a considerable part of the range indicated in Fig. 1.



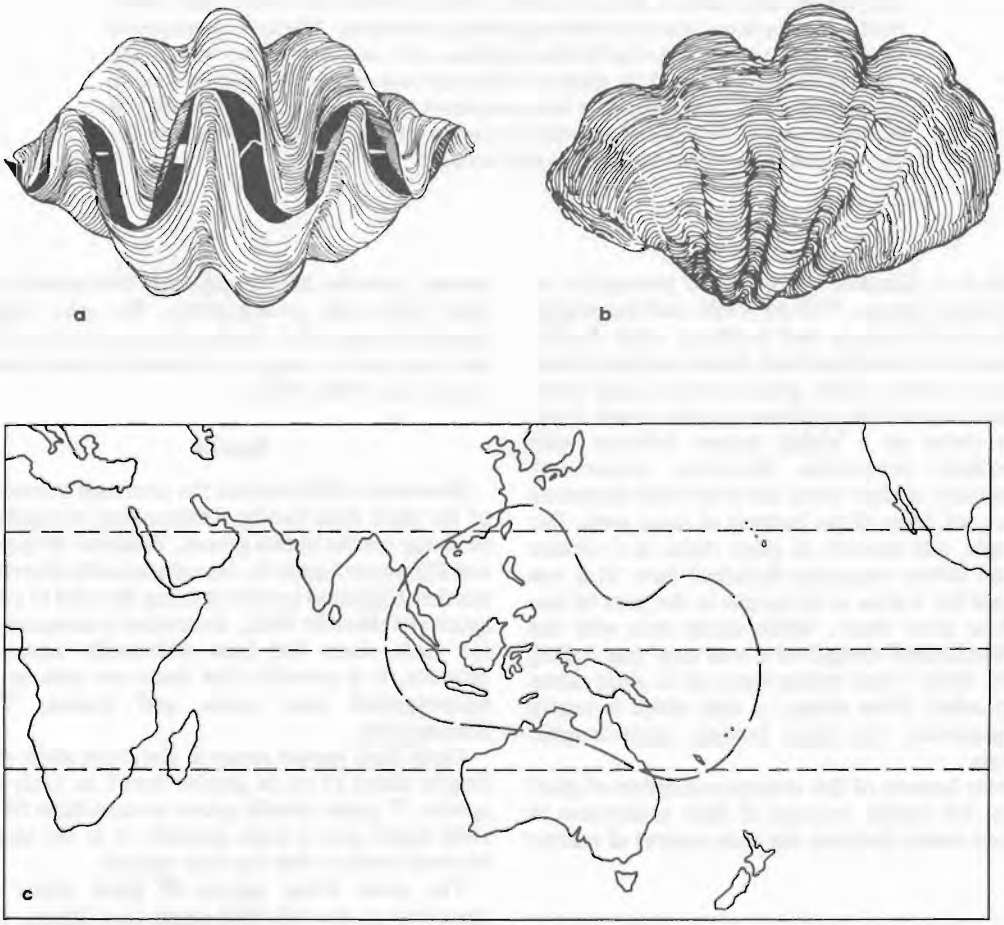
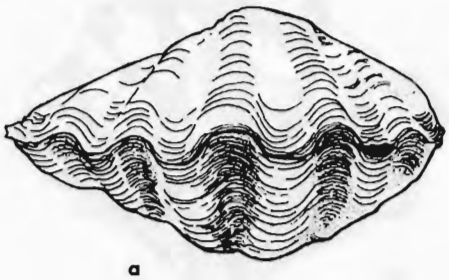


Fig. 1. *Tridacna gigas*: a. Upper view of large shells. b. Lateral view of shell. c. Geographical distribution. ***Photo:*** Large *T. gigas*, about 70 cm shell length, at Orpheus Island, North Queensland.

Tridacna derasa **(Smooth Giant Clam)**

This is the second-largest species (Fig. 2), with shell lengths up to 60 cm. It is distinguished by its heavy and very plain shells, without strong ribbing or scutes (scales). The mantle tends to have elongate patterns of colour which is sometimes brilliant blue.



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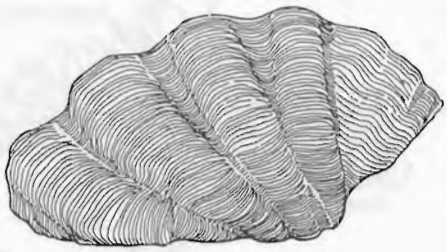

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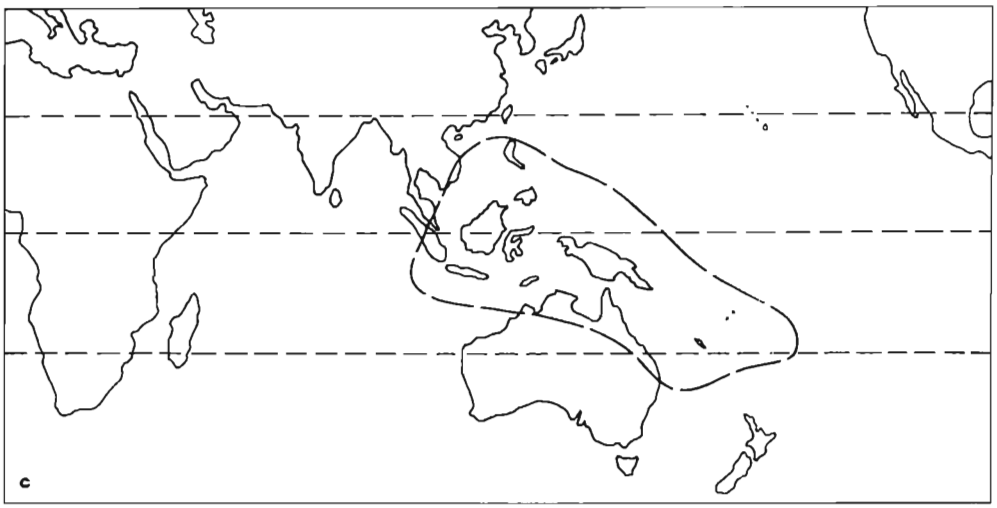
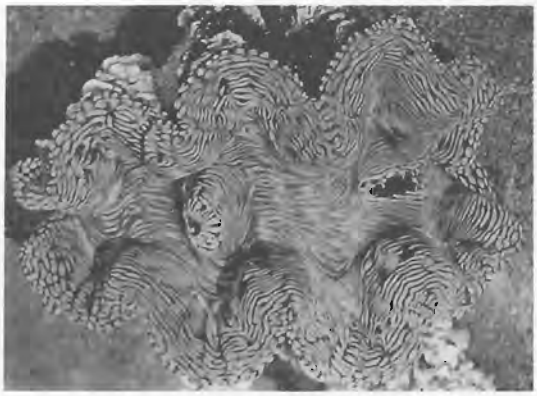


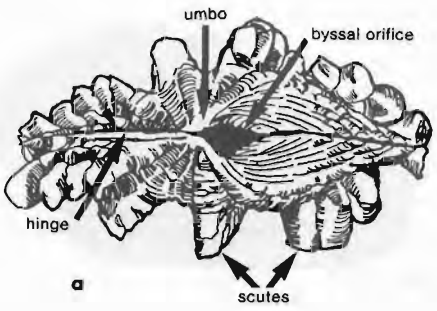
c

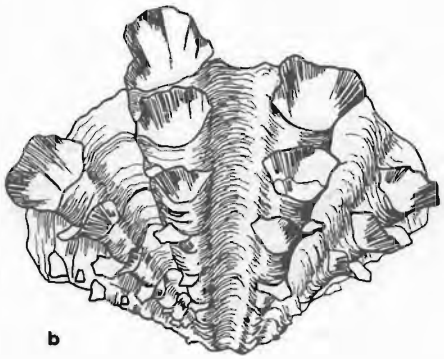
Fig. 2. *Tridacna derasa*: a. Upper view of shells. b. Lateral view of shell. c. Geographical distribution. ***Photo:*** Cultured specimens of *T. derasa* at MMDC, Palau.

Tridacna squamosa **(Fluted or Scaly Clam)**

This species is distinguished by its large, well-spaced scutes, and the shell length can reach about 40 cm (Fig. 3). The mantle tends to be mottled in various mixes of green, blue, brown, orange and yellow. Some shells are orange-pink in colour and have been highly prized in the Philippine shell trade.







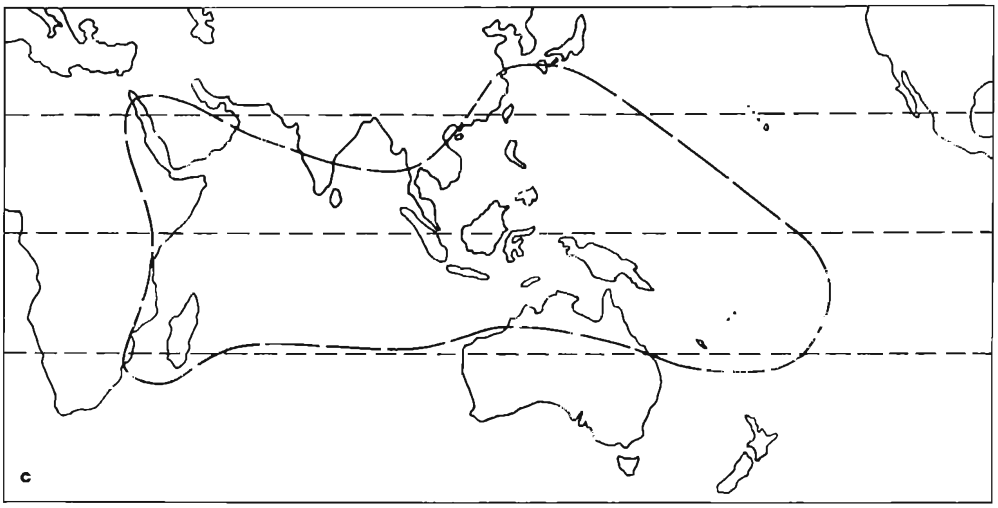


Fig. 3. *Tridacna squamosa*: a. Under view of shells. b. Lateral view of shell. c. Geographical distribution. ***Photo:*** *Tridacna squamosa* at Motupore Island, Papua New Guinea.

Tridacna maxima **(Great Clam or Rugose Giant Clam)**

The great clam is distinguished by its close-set scutes, and elongate byssal orifice compared to a short hinge, so that the shell is usually strongly asymmetrical about the umbo. The shell length reaches about 35 cm. The mantle is often brightly coloured and variable in colour and pattern. This is the most widely distributed species, with a geographic range extending from the western Indian Ocean to Polynesia (Fig. 4). It tends to bore into the reef, but is not usually as deeply imbedded as *T. crocea*. It reaches high densities in some parts of Polynesia, up to 60 clams/m^2, occupying virtually all of the available surface on some coral patches (Richard 1985) (photo opposite).

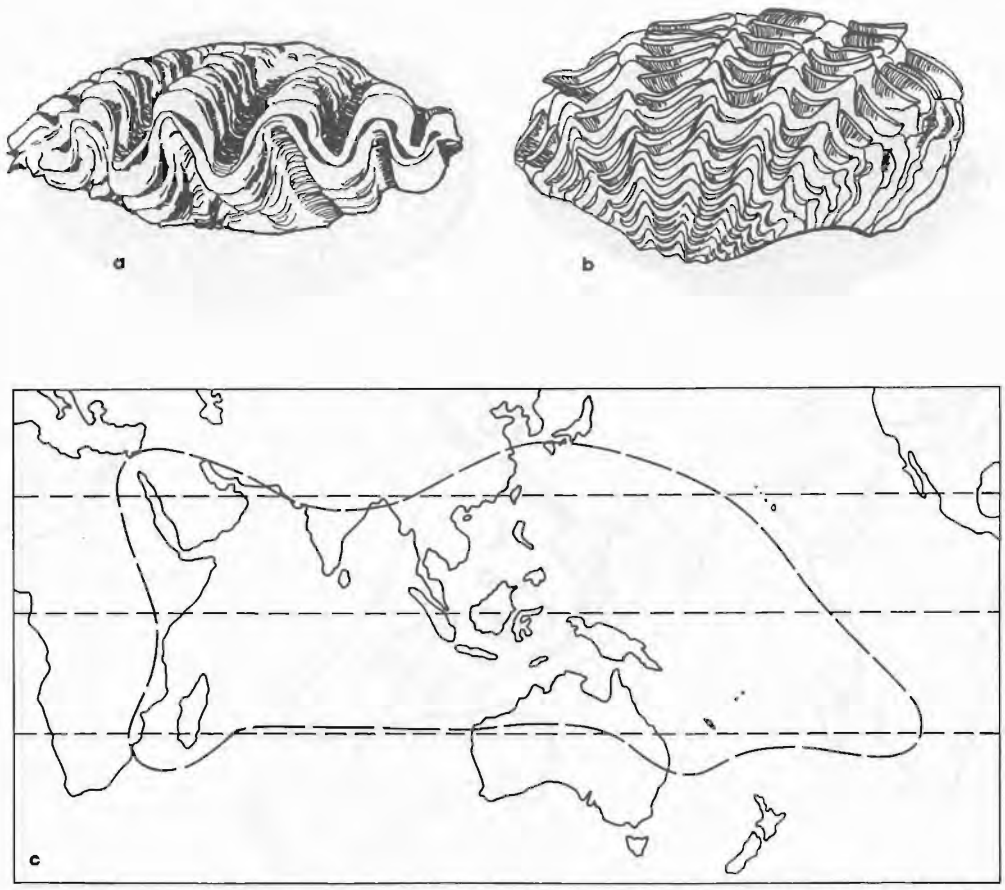


Fig. 4. *Tridacna maxima*: a. Upper view of shells. b. Lateral view of shell. c. Geographical distribution. ***Photo:*** High density of *T. maxima* in the lagoon of Takapoto Atoll, French Polynesia.

Tridacna crocea **(Boring or Crocus Clam)**

The smallest of the giant clam species (Fig. 5), *T. crocea* grows to a length of about 15 cm. The species is similar to *T. maxima*, but smaller, less asymmetrical and with its scutes worn away except near the upper edge of the shell. It bores into coral boulders and the reef to the upper margin of its shells. The mantle is usually brightly coloured, including green, blue, purple, brown and orange. This species tends to occur intertidally and reaches great densities at some localities. For instance in the Great Barrier Reef region it occurs at densities of more than 200 clams/m^2 on individual coral heads (Hamner 1978).

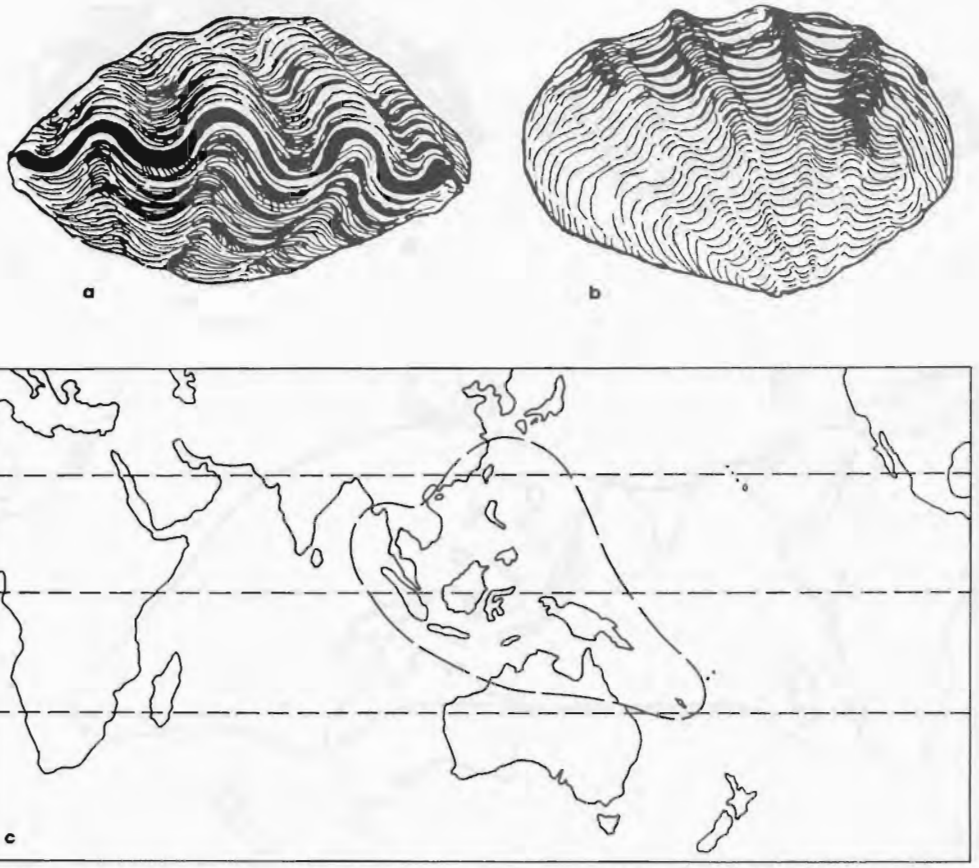
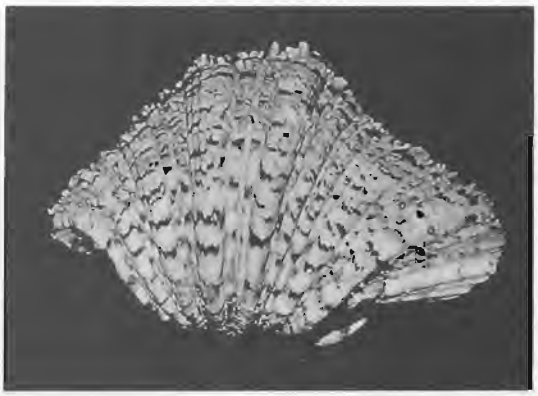


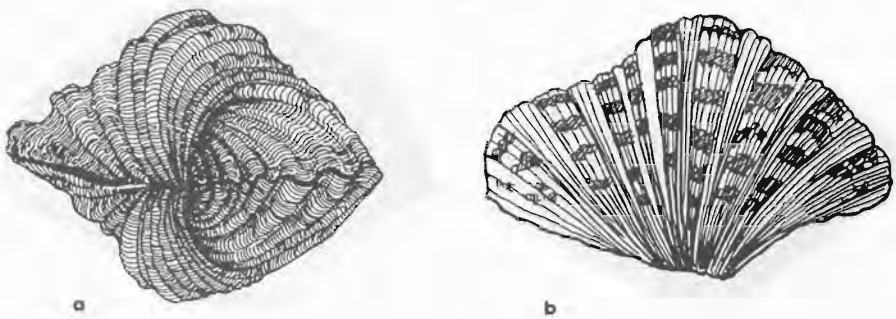
Fig. 5. *Tridacna crocea*: a. Upper view of shells. b. Lateral view of shell. c. Geographical distribution. ***Photo:*** *Tridacna crocea* at Orpheus Island, Great Barrier Reef.

***Hippopus hippopus* (Horse's Hoof, Bear Paw or Strawberry Clam)**

This species (Fig. 6) is distinguished by its heavy shells, which grow to a length of about 40 cm, with strong radial ribbing and reddish blotches in irregular bands. The mantle is yellow-brown, dull green or grey; dull in comparison to the *Tridacna* species.

The *Hippopus* species are readily distinguished from *Tridacna* species by their very narrow byssal orifice, which is closed with tight-fitting teeth (Fig. 7a), and by their mantle which doesn't project beyond the margins of the shells. In *Tridacna* species the byssal orifice is well developed and without tight-fitting teeth, and the extended mantle projects over the shell margins, so that the shells do not have to gape as much to expose mantle tissue as in *Hippopus* species.





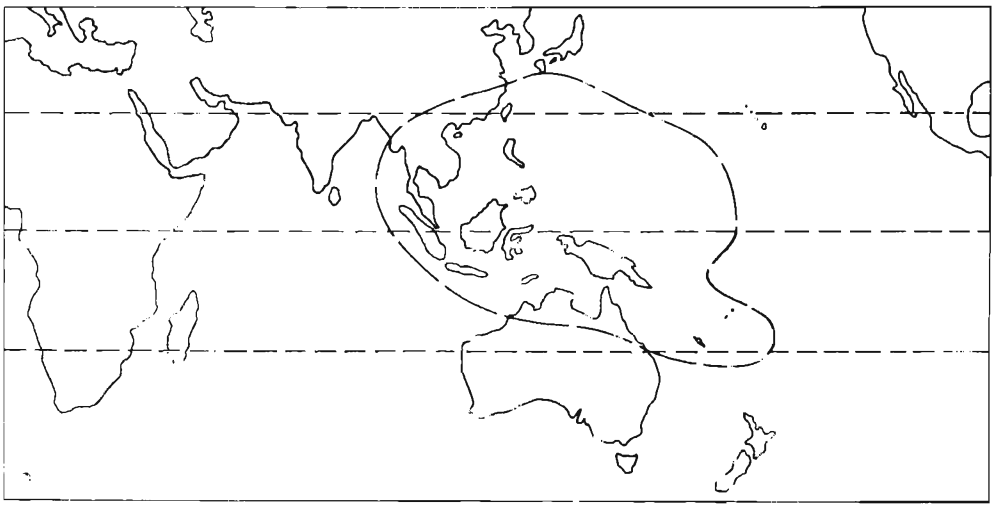


Fig. 6. *Hippopus hippopus*: a. Under view of shells. b Lateral view of small shell. c. Geographical distribution. ***Photo:*** A small *H. hippopus* from the Philippines.

Hippopus porcellanus **(China Clam)**

The shells of this species, which grow to a length of about 40 cm, are not as heavy or ribbed as *H. hippopus* in small specimens. The mantle colour is similar to *H. hippopus*. Rosewater (1982) distinguished this species from *H. hippopus* on its smoother and much thinner shells. He had access only to small shells of this species and in the largest individuals the shell differences are not as distinctive. One difference between the two species is that the incurrent aperture of *H. porcellanus* has fringing tentacles which are not present in *H. hippopus*. *Hippopus porcellanus* has the most limited distribution of the described species (Fig. 7), but has been a major target of the recent shell trade in the Philippines (Gomez and Alcala, These Proceedings).

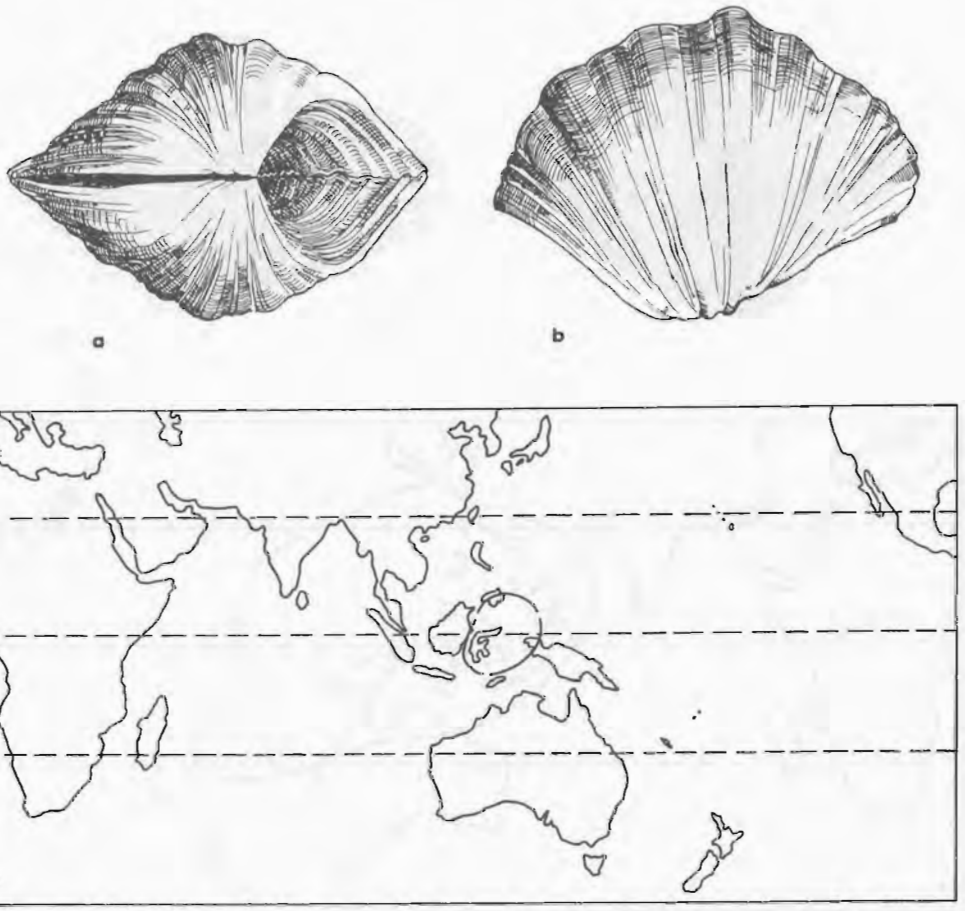


Fig. 7. *Hippopus porcellanus*: a. Under view of shells. b. Lateral view of small shell. c. Geographical distribution. *Photo:* Large individuals of *H. porcellanus* at MMDC, Palau.

Key to Species

The following key is based on shell and mantle characters, the latter being only applicable to live specimens.

1 With a well defined byssal orifice that does not have interlocking teeth (e.g. Fig. 3a). Mantle, when fully extended, projecting laterally beyond the shell margins . . . *Tridacna* species . . . 2

With a very narrow byssal orifice that is bordered by interlocking teeth (Fig. 7a). Mantle only reaching to the margins of the shells when fully extended . . . *Hippopus* species . . . 6

2(1) Shell length of large specimens greater than 50 cm. With about 4 elongate triangular projections of each upper shell margin; most elongate in large specimens (Fig. 1). Shells without scutes (scale-like projections), except for some tubular projections near the umbo in small specimens. Mantle brownish, with numerous iridescent blue-green circles . . . *T. gigas* (Fig. 1)

Shell length of large specimens very rarely greater than 50 cm. Without elongate triangular projections of each upper shell margin. Shells with or without scutes. Mantle variably coloured, without iridescent blue-green circles . . . 3

3(2) Shell length usually up to 50 cm, occasionally larger. Shells thick and plain, without scutes (except for tubular projections near the umbo in small specimens) or strong radial folds. Hinge usually longer than half shell length. Mantle often with bright colouration, tending to have elongate patterns of colour, sometimes brilliant blue . . . *T. derasa* (Fig. 2)

Shell length usually less than 40 cm. Shells with scutes, at least small scutes near shell margin; sometimes with strong radial folds. Hinge equal to or less than shell length. Mantle colourful or subdued . . . 4

4(3) Shell length less than 15 cm. Shells not strongly asymmetrical about the umbo in lateral view. Byssal orifice wide. Scutes low and only evident at the shell margins. Older scutes (back from shell margin) have been worn away. Occurs imbedded to the shell margins in coral boulders and reefs. Mantle brightly coloured, often with much colour variation between nearby specimens . . . *T. crocea* (Fig. 5)

Shell length up to about 40 cm. Shells variably symmetrical about the umbo in lateral view. Byssal orifice wide to narrow. Scutes present over much of shells. Occurs on surface to somewhat imbedded in the substrate. Mantle brightly coloured or subdued . . . 5

5(4) Shells often strongly asymmetrical about the umbo in lateral view, with hinge distinctly shorter than half shell length. Byssal orifice moderately wide to wide. Scutes usually low and set close together both within radial rows and between rows. The lateral distance between scutes in adjacent rows is usually much less than the scute width. Partially imbedded in the substrate. Mantle brightly coloured; incurrent aperture without tentacles . . . *T. maxima* (Fig. 4)

Shells approximately symmetrical about the umbo in lateral view, with hinge about half shell length. Byssal orifice narrow to moderately wide. Scutes large and well-spaced both within the radial rows and between the rows. The lateral distance between scutes in adjacent rows is usually about the width of the scutes. Not imbedded in the substrate. Mantle usually of subdued and mottled colouration; incurrent aperture with tentacles . . . *T. squamosa* (Fig. 3)

6(1) Shells thick and strongly ribbed, with reddish blotches in irregular bands. Incurrent aperture without tentacles . . . *H. hippopus* (Fig. 6)

Shells, in specimens less than about 20 cm length, not thick and strongly ribbed and with faint reddish blotches. Incurrent aperture with tentacles . . . *H. porcellanus* (Fig. 7)

Symbiosis and Morphology

The unique feature of giant clams among bivalve molluscs is their symbiotic relationship with dinoflagellate algae, zooxanthellae, in their mantle tissues. They retain the filter-feeding gills of normal bivalve molluscs, but their food intake from filter feeding is supplemented by nutrient molecules gained from the photosynthesis of the zooxanthellae (Griffiths and Streamer, and Fitt, This Monograph). This symbiosis has a profound effect on the ecology and morphology of giant clams. They are phototrophic and only found in shallow water, down to about 20 m depth in clear conditions. They occur at less depth in turbid conditions. Their tropical distributions may also relate to light, in that they may not tolerate the long periods of low sunlight during winter at high latitudes.

The morphology of giant clams is highly modified by great development of the siphon tissues to become the large mantle tissue containing symbiotic algae (Fig. 8). To achieve this has involved strong rotation of the body compared to the shell, turning the umbo and hinge to the underside of the body and presenting the hypertrophied siphon tissues uppermost to the sunlight (Yonge 1975). In this rotation process the anterior adductor muscle has been lost and the posterior pedal retractor muscle has been brought to be contiguous with the posterior adductor muscle (Fig. 8). It is these two large contiguous muscles that make up the highly prized 'adductor muscle' harvested from giant clams. However, all the soft tissues of giant clams are edible except for the kidney which accumulates arsenic and heavy metals (Benson and Summons 1981; Denton 1985).

This symbiosis with zooxanthellae is not unique. A number of other benthic coral reef invertebrates, including reef-building and soft corals, use this symbiosis with what is currently recognised as a

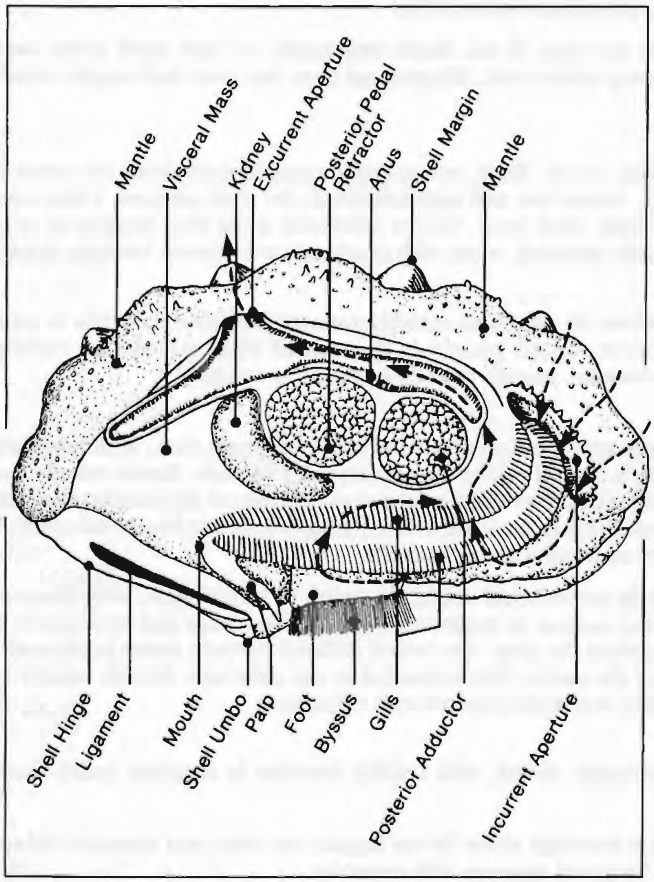


Fig. 8. A giant clam in lateral view with shell and mantle removed from one side to expose the body. Dotted lines show the water currents through the mantle chamber (redrawn from Yonge 1975).

single zooxanthellar species *Symbiodinium microadriaticum*. The major difference between giant clams and cnidarians (corals, etc.) is that in cnidarians the zooxanthellae are intracellular, while in giant clams they occur in the extracellular haemal sinuses of the mantle.

Various authors have commented on the relative importance of autotrophy and filter-feeding in giant clams. It is probable that this is not uniform during development nor between the various species, which differ vastly in size. Yonge (1975) suggested that sustenance from symbiotic algae has enabled giant clams to exceed the size limitations imposed by ciliary filter feeding and is the secret of their gigantism. If this is the case then it is possible that the largest giant clam species are most dependent on autotrophic nutrition. Recent studies have shown how dependent *T. gigas* is on high light intensities (see Lucas et al. and Mingoa, This Monograph).

Life Cycle

Adult giant clams are usually simultaneous hermaphrodites. They become sexually mature as males (protandry) at two or more years of age and subsequently become hermaphrodites with gonads containing spermatogenic and oogenic tissue in close proximity (see gonad histology figures in Nash et al., This Monograph). Breeding may extend throughout the year at lower latitudes, but at higher latitudes the clams tend to breed during summer months.

Despite the complex mixture of gametogenic tissue within the large gonad, the spermatozoa and ova are shed as separate events. Spermatozoa release precedes ova release by usually at least 30 min and often occurs without subsequent release of ova. This suggests that self-fertilisation is avoided. The act of releasing gametes is vigorous, with a series of strong expulsions through the excurrent aperture. Giant clams can respond to the presence of eggs in the water by sperm release within a few minutes. Thus, in natural populations there may be a chain reaction of clams detecting eggs, releasing sperm and then in turn releasing eggs which will stimulate other clams down-current.

The released eggs are about 100 μm diameter. The number spawned varies from unit millions in small clams like *T. crocea* to hundreds of millions in large individuals of *T. gigas*. They drift in the water column and undergo the characteristic embryonic development of molluscs. A ciliated trochophore larva hatches after about 12 hours and this develops into a bivalved veliger larva, about 160 μm shell length, two days after fertilisation. These larvae are typical bivalve mollusc larvae, having no zooxanthellae, and thus they filter-feed on phytoplankton, etc., for their nutrition.

The veliger larvae develop a foot (now called pediveligers) and alternate between swimming and being on the substrate. Their velum atrophies and they settle permanently onto the substrate about 9 days after spawning. The newly metamorphosed juvenile giant clams are about 200 μm shell length. They may attach to their substrate with a byssus, but they are not fixed in position in the initial weeks. They break the attachment and creep along the substrate with the shells upright and the foot extending and contracting. At this stage the symbiosis with zooxanthellae is established.

Unlike corals which pass zooxanthellae to their offspring during embryogeny, clam eggs and embryos have no zooxanthellae. Free-living zooxanthellae occur in the phytoplankton and if these are ingested by the filter-feeding larvae at least some resist digestion. These remain in the stomachs of the larvae and subsequent juvenile clams. The juvenile clams may also ingest zooxanthellae by their filter-feeding. These zooxanthellae move from the stomach into the sinuses of the juvenile clam's developing mantle and proliferate to form rows. The mechanisms by which zooxanthellae evade digestion and then pass from the stomach to the mantle have yet to be clarified (see Heslinga and Fitt 1987). However, the symbiosis is established very soon after metamorphosis and the giant clam's phototrophic mode of life commences.

The initial growth rates of giant clam juveniles are slow in absolute terms. They take several months or more to reach several millimetres shell length. They may be 20–40 mm shell length after a year. Thereafter, growth is rapid in the larger species. Growth is strongly influenced by a number of environmental factors, but as a rule the larger the species the more rapid is growth (Munro and Heslinga 1983). This is contrary to a prevalent view that giant clams are so large because they live so long. The growth curves for giant clams are sigmoidal, as for many other marine invertebrates, with the lower inflection point at about 1 year old. There are some years of rapid growth before the growth rate tapers off, possibly associated with the onset of substantial oogenesis.

The smaller species of giant clams, *T. crocea*, *T. maxima* and *T. squamosa*, remain attached to the substrate throughout their lives. The other four species grow beyond byssal attachment and rely on heavy shell thickening near the umbo to give them stability and to keep them oriented with the mantle uppermost.

Estimations of the life-spans of giant clams have been speculative and ranged up to several hundred years (Rosewater 1965). Clams form seasonal growth bands in their shells, and it is therefore possible to age sections of dead shells. This gives promise of more reliable data on growth and

longevity. Giant clams may live for several decades or more. The oldest reliably dated clam is a large specimen of *T. gigas* which has more than 50 annual growth bands in cross-section (C.C. Shelley, pers. comm.).

Mariculture

Because giant clams have larval stages that are typical of bivalved molluscs, the hatchery methods that have been developed for other commercial bivalves, e.g. oysters and scallops, are applicable to them. These hatchery methods may be extensive, such as have been used by Heslinga and co-workers at the Micronesian Mariculture Demonstration Center, or they may be intensive (see Braley et al., This Monograph).

The need for innovative culture methods arises after metamorphosis when the juvenile giant clams begin their phototrophic mode of life. Many of the methods for mass-culturing commercial bivalves involve three-dimensional systems, e.g. upwelling systems for culturing multiple layers of small oysters in nursery tanks and stacks of suspended plates or racks in field culture. Giant clams require two-dimensional culture systems as upper layers will shade under-layers causing stunting or death of under-layer clams.

In common with other bivalves, giant clams are subject to heavy predation in the field when small and are less prone to predation as they increase in size. Thus, there is a progression of culture methods reflecting the changing level of protection against predators that is needed. Crawford et al. (1988) recognised four phases in the culture of giant clams:

1. Hatchery Phase — rearing larvae from eggs in indoor or outdoor tanks;
2. Nursery Phase — rearing juvenile clams in onshore tanks from metamorphosis (0.2 mm shell length) to about nine months of age and 20+ mm shell length ('seed' clams);
3. Ocean-Nursery Phase — rearing juvenile clams in protective containers in the field from about 20 mm shell length to 200+ mm shell length;
4. Grow-Out Phase — rearing clams, 200+ mm shell length, without protection in the field.

Exploitation and Conservation

The peoples of the Pacific and Southeast Asia have traditionally harvested giant clams for their meat and shells. There is, however, evidence of widespread overfishing of giant clams in recent times even by traditional consumers. This is partly due to population increases and technological advances. Use of goggles and masks underwater and power boats has enabled access to giant clam stocks that were previously inaccessible through depth or remoteness. Another factor in the decline of giant clam populations is a general deterioration of coral reef environments in some regions.

Clam poaching by foreign fishermen has been important in the decline of stocks of the largest species, *T. gigas* and *T. derasa* (Dawson, This Monograph).

In recognition of the endangered status of these two largest species over much of their ranges, they were proposed and accepted for listing on Appendix II of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) (IUCN 1983). This 'would not interfere with mariculture efforts or attempts to improve harvests for local people, but would enable international trade in shells to be monitored and controlled.' Subsequently the parties to CITES accepted a proposal to list all seven giant clam species on Appendix II of the Convention.

The Great Barrier Reef contains six giant clam species and is a large region of protection for giant clams. Only traditional users are permitted to exploit giant clams and they do not access large areas of the reef. It is unfortunate that the most hard-pressed giant clam species, *H. porcellanus*, is the one species not occurring in the Great Barrier Reef region.

Recent Research

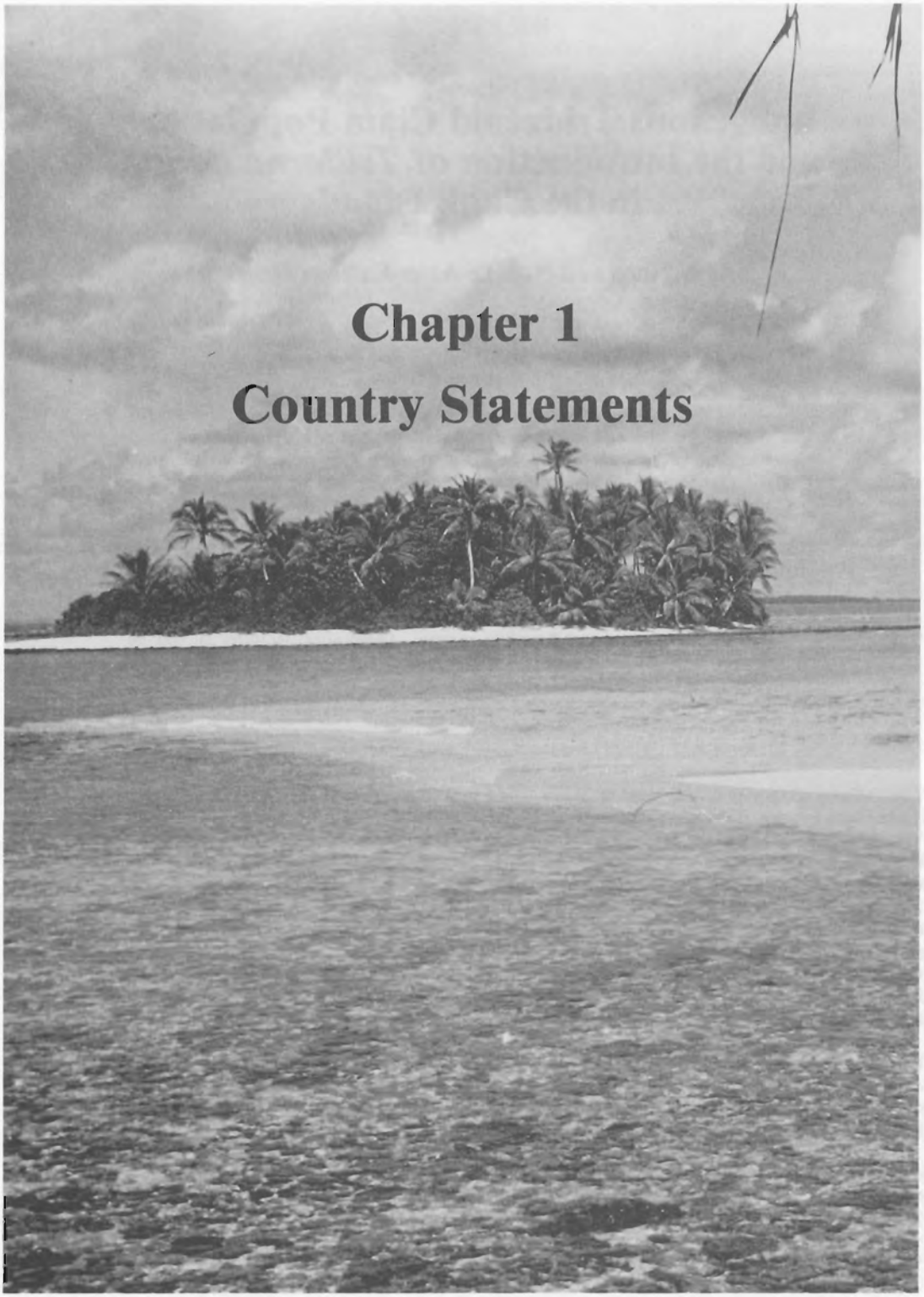
There has been a surge of research interest in giant clams over the past two decades. This has come about:

- for academic reasons: through final realisation of their unique characteristics among bivalve molluscs (although their symbiosis was identified by Yonge in the 1930s);
- for pragmatic reasons: through recognition of the widespread overexploitation of giant clams and of their potential for mariculture.

This surge of research is clearly shown in the bibliography of giant clam literature of Munro and Nash (1985). More than 70% of the 290 references listed appeared since 1970. In the period 1900–69 the publication rate on giant clams averaged only one paper per year. There are more papers in this present volume than were published on giant clams in the first 60 years of this century.

Acknowledgments

I wish to thank Mrs Robyn Gracie for her invaluable assistance in the organisation and conduct of the workshop. The species illustrations were drawn by Benny Lynch and Jane Kennedy and are used with the permission of the Australian National Parks and Wildlife Service. I dedicate this paper to the memory of my father, John S. Lucas Snr, who died recently while I was engaged in the editorial work for this book.



Chapter 1
Country Statements

Indigenous Tridacnid Clam Populations and the Introduction of *Tridacna derasa* in the Cook Islands

Neil A. Sims and Ned Te-Atua-Katinga Howard*

Abstract

Surveys of *Tridacna maxima* stocks were conducted on four atolls in the Cook Islands to estimate densities and size-class distribution. Predation appears to limit clam abundance in larger, open lagoons. Stocks of *T. maxima* on smaller atolls, and high islands in the Southern Group, are limited by heavy fishing pressure. *Tridacna squamosa* is found only rarely on the outer reef slopes of Rarotonga and Aitutaki.

One thousand juvenile *T. derasa* were introduced to Aitutaki in May 1986. Heavy predation by *Cymatium muricinum* ensued. These mortalities, combined with losses from cyclone damage, meant that only 200 survived after 1 year. Rates of shell length increase were monitored for these clams, allowing estimation of growth coefficients.

Developments of tridacnid clam stocks in the Cook Islands should be based on the establishment of permanent breeding reserves. Quarantine facilities should be established, and used both for further introductions, as advisable, and for small-scale hatchery culture of *T. derasa*, *T. squamosa*, and, potentially, *T. gigas*.

Two indigenous species of tridacnid clams are found in the Cook Islands. *Tridacna maxima*, the smaller 'rugose' clam, is abundant in the lagoons of the larger atoll islands, where it is the most significant shellfish component of local subsistence diets. *Tridacna maxima* is less common on smaller atolls such as Pukapuka and Rakahanga, and on the more populated high islands in the Southern Group, which only possess narrow bench or fringing reefs. In such instances, both environmental constraints and fishing pressure appear to limit its abundance.

Tridacna squamosa, the 'fluted' clam, is rarely found on the outer reef slopes of Rarotonga and Aitutaki. Its distribution is generally limited to depths greater than 10 m, although this is likely due to higher fishing pressure in shallower waters.

Recent developments in hatchery culture of giant clams have aroused considerable interest in the Cook Islands. In May 1986 a shipment of juvenile *T. derasa* was purchased from MMDC, Palau, and air-freighted to Aitutaki. This represented the first introduction of *T. derasa* beyond its natural range in Polynesia.

This paper reviews the status of both indigenous and introduced giant clams in the Cook Islands. Data are presented on the abundance, distribution and population structure of *T. maxima* from several islands. The growth rates and mortalities of the introduced *T. derasa* are also reported. The future of tridacnid introductions, and potential for small-scale mariculture of giant clams in the Cook Islands are reviewed, and appropriate recommendations made.

Methods

Tridacna maxima

Density and population data for *T. maxima* were obtained from three Northern Group atolls (Suwarrow, Manihiki, and Penrhyn). The surveys were targeted towards assessing black-lip pearl-oyster (*Pinctada margaritifera*) stocks, and as such, the methods employed and areas surveyed were

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dependent on pearl-oyster distribution patterns. The clam data were collected only incidentally.

Swathe transects, varying between 1 and 4 m wide (depending on depth, substrate rugosity, and pearl-oyster density) were randomly sited throughout each of the lagoons, and surveyed by scuba-diving. Each of the clams within the swathe boundaries was counted and measured to the nearest centimetre by divers working along the transect rope. Twenty-four stations were surveyed in Suwarrow, 17 in Manihiki, and 11 in Penrhyn. Stocks on the reef flat or outer reef slope were not surveyed. Figure 1 (a-d) shows the location of survey sites within each of the lagoons.

In Aitutaki, *T. maxima* were surveyed on the reef flat at three locations, and at one station in the deeper part of the lagoon. The reef flat stations consisted of arbitrarily selected sites on the barrier reef. At each station, a quadrat of 1 m^2 was randomly placed 10 times within each of the different reef zones. At the lagoon station, samples were taken on the top of a nearby ribbon reef, and around the base of the ribbon reef and nearby coral heads, in water from 3 to 5 m deep. All of the *T. maxima* within each quadrat were counted, and measured with calipers.

Tridacna derasa

The *T. derasa* introduced to Aitutaki were originally held in plastic mesh trays in a channel between two lagoon-rim islets. Following heavy infestation by *Cymatium muricinum* predatory

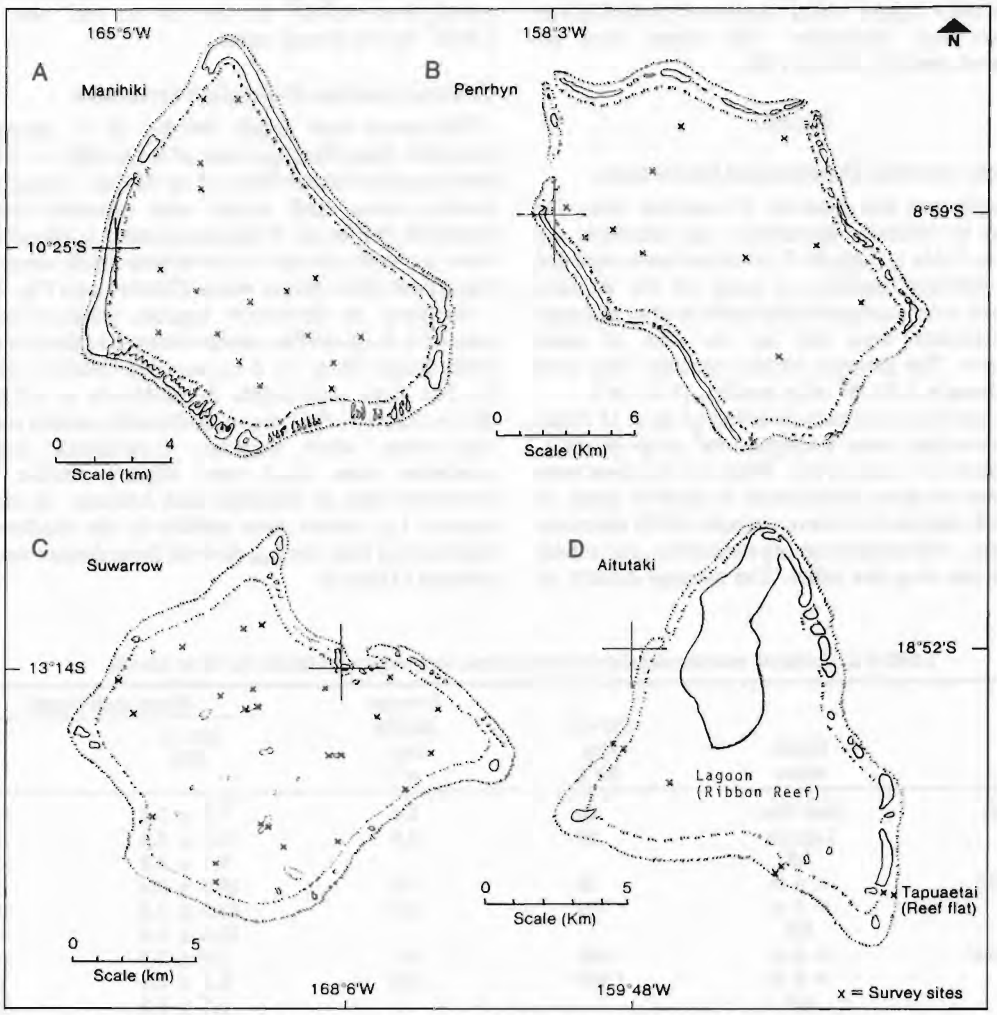

Fig. 1. Location of survey sites within the four lagoons: A, Manihiki; B, Penrhyn; C, Suwarrow; and D, Aitutaki.

gastropods, the trays were relocated several times. In a continuing effort to minimise *C. muricinum* attacks, the trays were finally placed on a raised platform, 2 m above the substrate. Mortalities declined to negligible levels soon after.

The spawning dates for each of the two batches of *T. derasa* had been recorded by MMDC personnel, who had also measured shell lengths for samples of 50 clams from each batch immediately before shipment. In Aitutaki, it was intended that mean growth rates be monitored by keeping the clams in numbered trays, with each batch separated. Unfortunately, heavy seas associated with cyclones during January 1987 upturned the trays and scattered the clams, before any worthwhile re-measurements could be obtained. Growth data thereafter, then, represent pooled results for both batches. In May 1987 all remaining clams were remeasured using stainless steel calipers, and individually tagged using numbered polyethylene markers and 'superglue.' The clams were re-measured again in March 1988.

Results

Tridacna maxima: Densities and Distribution

Density and size data for *T. maxima* from the surveys in Aitutaki, Suwarrow, and Manihiki are given in Table 1. Only 14 *T. maxima* were recorded from Penrhyn lagoon, as most of the stations surveyed there were of considerable depth, and only two transects were laid up the face of coral pinnacles. The greatest density recorded was only nine clams in a 20 m^2 strip quadrat (0.45/m^2).

In Manihiki, maximum densities of up to 15 clams were recorded from a single 5 m^2 strip quadrat, equivalent to 3 clams/m^2. *Tridacna maxima* were observed on some coral-heads in shallow areas of Manihiki lagoon to achieve virtually 100% substrate coverage, with clams abutting each other, and others settled one atop the other. The average density of *T. maxima* in the upper 6 m depth stratum for all substrate types in Manihiki lagoon was almost 1.9/m^2. *Tridacna maxima* was also common at greater depths, with a maximum density of 13 clams in one 10 m^2 strip quadrat at 12.2 m depth (1.3/m^2), and with three clams recorded from a depth of 23.7 m.

In Suwarrow lagoon, a single 4 cm clam was recorded from 32 m depth, with an average density of 0.04 clams/m^2 from the 12.1–24.3 m depth strata. Clam densities in Suwarrow lagoon were less than that for Manihiki, with a maximum of 1.9/m^2 recorded from a single 20 m^2 strip quadrat.

On the reef flat in Aitutaki, a maximum density of 25 clams was recorded from a single square metre quadrat at Tapuaetai. The average density on the reef flat at Tapuaetai (5.4/m^2) was significantly greater than that from the other reef flat stations (0.09/m^2). At the lagoon station, average densities varied from 4.7/m^2 on the ribbon reef top, to 1.0/m^2 for the deeper areas.

Tridacna maxima: Population Structures

The mean shell length for the 14 *T. maxima* recorded from Penrhyn was 14.0 cm (SD = 2.2). Shell lengths ranged from 11 to 19 cm. A slightly smaller mean shell length was recorded from Manihiki (Table 1). *Tridacna maxima* in Manihiki were markedly smaller in the 0–6 m depth stratum than those from deeper water (Table 1 and Fig. 2).

Similarly, in Suwarrow lagoon, shallow-water clams (< 6 m) exhibit smaller mean size than those from deeper water (> 6 m) samples (Table 1, Fig. 3). The mean shell length in Suwarrow of 6.2 cm (SD = 3.2; n = 199), was considerably smaller than that from other lagoons. Calculated mean maximum sizes (L_∞) were slightly smaller in Suwarrow than in Manihiki and Aitutaki. In each lagoon, L_∞ values were smaller in the shallower depth strata than the L_∞ derived from deeper water samples (Table 2).

TABLE 1. *Tridacna maxima* density and mean sizes with respect to depth for three islands.

Island	Depth strata	Survey area (m^2)	Average density (no./m^2)	Mean shell length (cm ± SD)	n
Aitutaki	Reef Flat	60	5.4	7.9 ± 3.3	275
	Lagoon	20	2.9	12.4 ± 3.8	104
	All			9.1 ± 3.9	379
Manihiki	< 6 m	30	1.9	10.6 ± 3.4	56
	> 6 m	795	0.2	12.7 ± 2.6	181
	All			12.2 ± 2.9	237
Suwarrow	< 6 m	260	0.5	5.9 ± 2.8	142
	> 6 m	1 980	0.0	6.8 ± 4.1	54
	All			6.2 ± 3.2	196

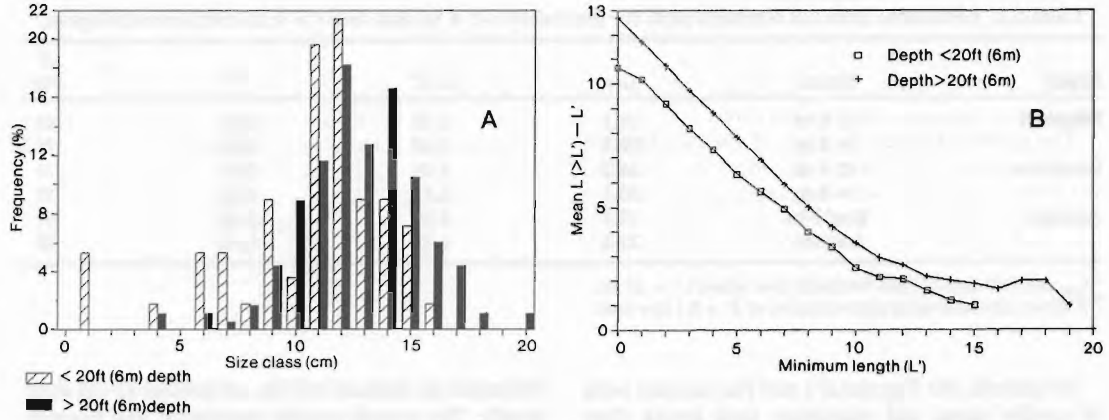

Fig. 2. Size-frequency distribution (A), and the Wetherall plot L^1 vs L(avg)-L^1 (B) for *T. maxima* at Manihiki.

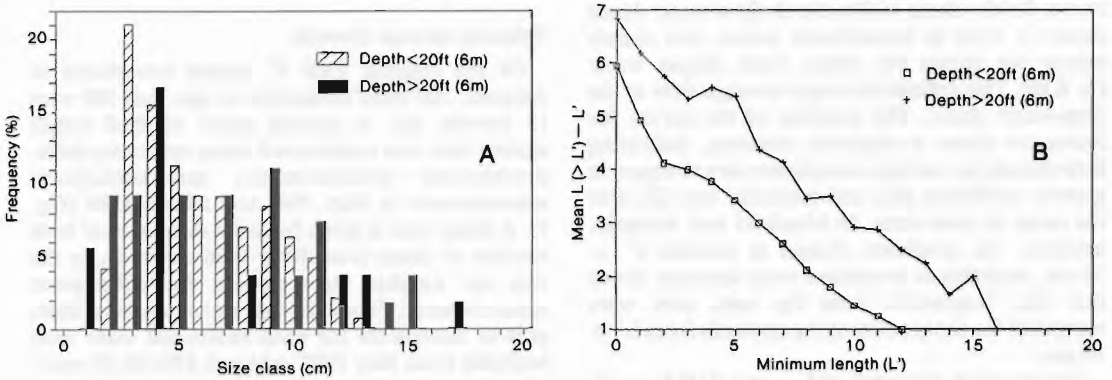

Fig. 3. Size-frequency distribution (A) and the Wetherall plot L^1 vs L(avg)-L^1 (B) for *T. maxima* at Suwarrow.

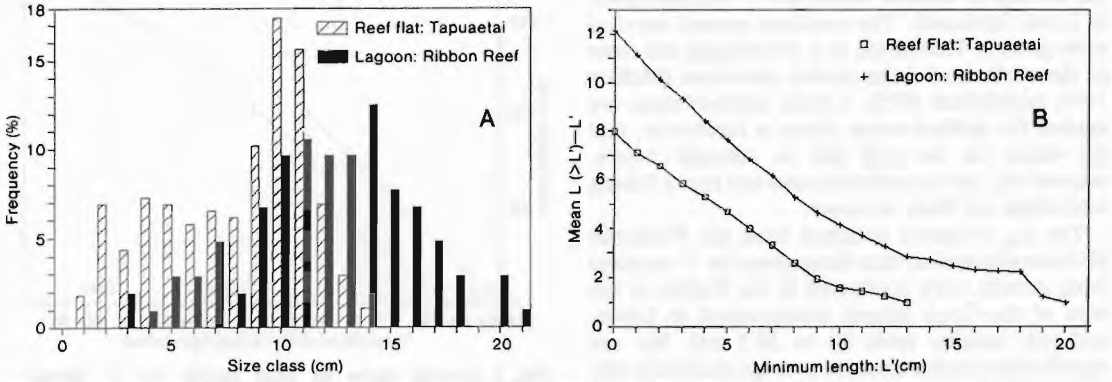

Fig. 4. Size-frequency distribution (A) and the Wetherall plot L^1 vs L(avg)-L^1 (B) for *T. maxima* at Aitutaki.

TABLE 2. Derivations from the Wetherall plots for the shallow (< 6 m) and deep (> 6 m) strata in each lagoon.

Island	Strata	$L\infty$	Z/K[a]	Z[b]	S (%)
Manihiki	< 6 m	18.1	2.22	0.22	80
	> 6 m	22.5	2.85	0.28	75
Suwarrow	< 6 m	16.2	3.35	0.35	70
	> 6 m	20.1	2.33	0.23	79
Aitutaki	Reef Flat	18.1	4.00	0.40	67
	Lagoon	23.2	2.22	0.22	80

[a] L_∞ and Z/K derived from Wetherall plots where L^1 > 10 cm.
[b] Z values calculated using approximation of K = 0.1 (see text).

In Aitutaki, the Tapuaetai's reef flat samples were of smaller mean and maximum shell length than those from the lagoon ribbon reef (Fig. 4).

Wetherall plots were constructed for *T. maxima* shell lengths for each of the two depth strata within each of the lagoons (Wetherall 1986; Pauly 1986; and Pearson and Munro, in press). In each of these plots, displayed in Fig. 2(b), 3(b) and 4(b), the curves for the clams within the shallow-water depth strata (< 6 m) lie immediately below, and closely mirror the curves for clams from deeper water (> 6 m). This reflects the larger average sizes of the deep-water clams. The gradient of the curves for Suwarrow clams is relatively constant, indicating little change (or perhaps complementary changes) in growth coefficient (K), and mortality rate (Z) over the range of clam sizes. In Manihiki and Aitutaki, however, the gradients change at around L^1 = 10 cm, probably as predation rates decrease above this size. Regression lines for each plot were computed for those points lying upwards from L^1 = 10 cm.

The resulting estimates of $L\infty$ and Z/K for each plot are given in Table 2. Comparison of mortality rates between depth strata and between lagoons can be approximated by assuming that K values are constant in each case, and letting K = 0.1. This value of the growth coefficient was estimated from the average of those K values for *T. maxima* given in Lewis (undated). The resultant annual survival rates given in Table 2 (S, as a percentage) are close to those obtained from studies elsewhere (McKoy 1979; McMichael 1975). Lowest survival rates are evident for shallow-water clams in Suwarrow, and for clams on the reef flat in Aitutaki where, respectively, heavy predation rates and heavy fishing mortalities are likely to occur.

The $L\infty$ estimates obtained from the Wetherall plots are slightly less than those given for *T. maxima* from growth work conducted in the Pacific to the west of the Cook Islands (summarised in Lewis, undated; ranging from 22 to 30.5 cm), but are significantly greater than the average maximum size estimated from Takapoto lagoon in French Polynesia by Richard (1978), of around 12 cm shell length. The overall smaller maximum and average sizes of *T. maxima* in the Cook Islands and French Polynesia, compared with populations from further west, has been noted elsewhere (Lewis, undated). Correspondingly higher densities are found within this Eastern Polynesian range, compared with elsewhere in the Pacific (Lewis, undated).

Tridacna derasa: Growth

Of the original 1000 *T. derasa* introduced to Aitutaki, 500 were 18 months of age, and 500 were 13 months old. A growth curve of shell length against time was constructed using spawning dates, preshipment measurements, and subsequent measurements in May 1987 and March 1988 (Fig. 5). A single plot is given from the mean size of both batches of clams from May 1986 onwards, as the two age batches were pooled for subsequent measurements. From the tag and remeasure data, growth increments for each individual clam were available from May 1987 to March 1988 (0.79 year). These were plotted on a Ford-Walford plot (Fig. 6), giving a line of best fit of formula Y = 0.875 X + 57.3 (r = 0.658). Corresponding estimates of

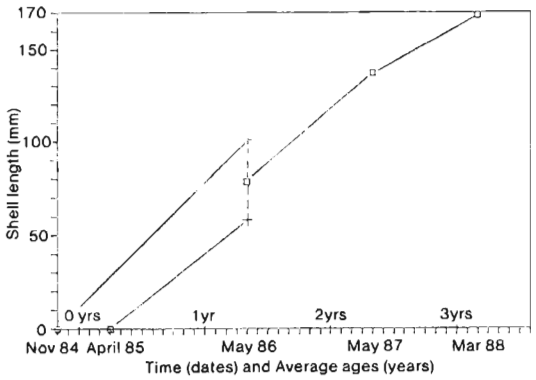

Fig. 5. Growth curve of shell length for *T. derasa* introduced to Aitutaki in June 1986.

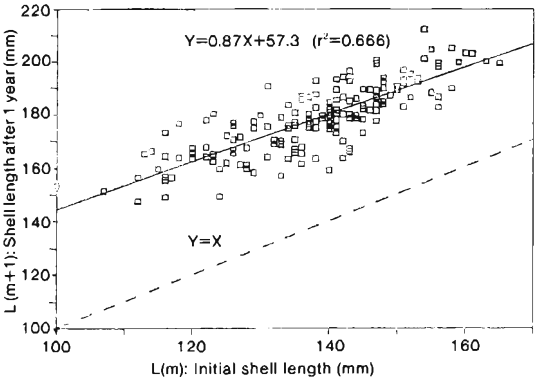

Fig. 6. Ford-Walford plot of growth increments of the *T. derasa* of Fig. 5.

growth coefficients were obtained such that L_∞ = 458 mm, k (Ford's growth coefficient) = 0.875, and therefore K (Brody-von Bertalanffy growth coefficient) = 0.1335.

The broad spread of points about the plot-line in Fig. 6 suggests a varying growth rate between individual clams. Calculated annual increments ranged from 19 mm/year to 60 mm/year, with a mean of 40.2 mm/year (SD = 7.6; n = 179). Analysis of annual increments for each size-class showed that smaller (120–124.5 mm) *T. derasa* averaged 49 mm/year, although no overall relationship was found between size-classes and mean annual shell length increment.

Tridacna derasa: Mortality

Only 34 of the *T. derasa* died during, or immediately after, shipment. In the first 2 months, however, a further 24.6% mortality occurred. A number of *Cymatium muricinum* were found within the dead or dying clams, with eight snails found in a single 84 mm *T. derasa* specimen. A maximum size of 22 mm shell length was recorded for the *C. muricinum*, indicating an approximate age of around 2 months (based on the von Bertalanffy curve given by Perron et al. 1985). Infestation of the clams must have begun almost immediately after the clams were placed in Aitutaki. Heavy mortalities continued from August through to November 1986, before abating.

Large numbers of clams were also lost during Cyclones Sally and Willy, in January 1987, and only 199 *T. derasa* remained in May 1987. These clams were then placed on the raised platform, and only 5.5% mortality occurred between May 1987 and March 1988. Each of these was attributable to *C. muricinum*, although there was no marked seasonality to the infestation as had been observed for 1986. The decline in mortality could have been due to either the new location of the clams, the use of the raised platform, or the increased natural resistance of the clams as they approached the reported size of immunity to infestation of around 150 mm shell length (Perron et al. 1985).

Discussion

Tridacna maxima

The pattern of larger *T. maxima* shell sizes in deeper lagoon areas is most likely attributable to high mortalities of clams in shallower waters. In Aitutaki, where *T. maxima* stocks are heavily exploited, the observed smaller shell lengths on the reef flat are probably attributable to greater fishing mortality. In the uninhabited atoll of Suwarrow, the relatively lower *T. maxima* densities and overall smaller mean shell size is due entirely to natural mortalities. Black-lip pearl-oyster stocks in Suwarrow suffer severe predation rates from fishes and octopuses (Sims 1988), and the abundance of molluscivorous fishes in the open lagoon probably has similar impact on *T. maxima* stocks. Although Penrhyn Island is inhabited, the extensive lagoon also possesses a great abundance of large molluscivorous fishes. Again predation, rather than fishing pressure, appears to limit the *T. maxima* abundance in Penrhyn.

Conversely, the reefs and lagoons of both the smaller atolls of Pukapuka and Rakahanga, and the high islands of the Southern Group, are intensively fished. As the abundance of natural predators is thereby constrained, the scarcity of *T. maxima* on these islands is largely due to fishing pressures. Rakahanga lagoon provides an interesting example of apparent decline of *T. maxima* stocks, along with those of other bivalves (e.g. *Pinctada maculata*). In the past, 20–30 years ago, various bivalves were reportedly common inside the lagoon. *Tridacna maxima* are now found only rarely on the outer fringing reef. The decline in clam and other bivalve stocks evidently coincided with increased sedimentation of the main lagoon drainage channel, and increased turbidity of the lagoon waters. *Tridacna maxima* has been reintroduced to the lagoon, but no spatfalls have been evident.

Tridacna derasa

The growth rate for the *T. derasa* introduced to Aitutaki is only slightly less than that reported elsewhere in the literature. Beckvar (1981) and Heslinga and Watson (1985) report annual shell length increments of 5.8 cm/year (for clams of 13 cm mean length) and 5 cm/year (for a wide range of lengths), respectively. Growth parameters calculated for wild stocks of *T. derasa* on the Great Barrier Reef, of L_∞ = 46.9 cm, and k = 0.108,

with an average increment of 4.5 cm/year for clams in the 12–15 cm size-class (Pearson and Munro, in press), are comparable with those determined here.

The mortalities suffered from *C. muricinum* attacks are well above those reported elsewhere (Perron et al. 1985). It was previously concluded that these mortalities were exaggerated by an ineffective maintenance and caretaking program (Sims, unpublished report). This emphasises the need for regular, careful checking of outgrowing clams, as recommended by Perron et al. (1985).

Developments and Recommendations

With the heavy fishing pressure on *T. maxima* stocks on smaller atolls and high islands, some conservation measures are necessary. The slow growth rate of *T. maxima* suggests that clams are probably optimally harvested at relatively small sizes. Overfishing of recruits will then be the major concern. Permanent breeding reserves should therefore be established for clams on each island, to ensure continuing, self-sustaining recruitment.

On Rarotonga, attempts have recently been made to enhance *T. squamosa* recruitment by collection of adult specimens from beyond the reef, and holding them in close proximity to each other in the lagoon. Some poaching occurred, unfortunately, but the program is continuing under tighter security.

Although the *T. derasa* introduction has been initially successful, the long-term value of the program will only become evident with establishment of self-sustaining wildstocks. Again, however, subsistence fishing pressures will be such that a system of permanent reserves and/or artificially aggregated broodstocks will be necessary.

With the economic viability of intensive culture of *T. gigas* still under question, there appears to be no immediate need for introducing this larger species to the Cook Islands. Indeed, the evidence of great variability in growth rates of individual *T. gigas*, and potential for faster-growing *T. gigas* to be selectively bred (Pearson and Munro, in press), is a strong argument for restraint with introduction programs.

Other arguments must also be considered, however, and it is likely that further introductions of either *T. derasa* or *T. gigas* will be conducted. It is considered, then, imperative that some form of quarantining be guaranteed for each further introduction. An appropriate small-scale quarantine facility could also be used for hatchery culture of either the introduced clams, or as an upgraded recruitment enhancement program for *T. squamosa*. With resulting seed stock aggregated into the proposed permanent breeding reserves, resulting benefits would be both more immediate, and of greater significance, than the current reliance on natural recruitments.

Conclusions

Tridacna maxima stocks are relatively abundant on most of the atoll islands of the Cook Islands. On the smaller atolls and the high islands of the Southern Group, *T. maxima* stocks are heavily fished. Permanent breeding reserves should be established on these islands.

The introduced *T. derasa* suffered severe mortalities from *C. muricinum* predation, but exhibit healthy growth rates. The establishment of small-scale quarantine facilities is an essential prerequisite before further introductions are considered. *Tridacna gigas* introductions should not be undertaken until more information and quarantine facilities are available.

Acknowledgments

Dr A.D. Lewis enthusiastically provided guidance and assistance in all stages of this work. Dr G.A. Heslinga, and the MMDC staff provided training for NTK, and supplied the original *T. derasa* data along with the clams. The JCUNQ/ACIAR project also provided training for NTK.

Reintroduction of Giant Clams to Yap State, Federated States of Micronesia

C.M. Price and J.O. Fagolimul*

Abstract

This project was an attempt to reintroduce *Tridacna derasa* to Yap Proper. The primary goal of this project was to reseed Yap reefs with clam broodstock. Successful culture of *T. derasa* at the Micronesian Mariculture Demonstration Center in Palau, and 100% survival of clams in shipment by air, has resulted in an ocean-based survey for clam grow-out in Yap Proper. After 12 months of cage culture in Yap, the clams were distributed to 31 sites around Yap Proper. *Tridacna derasa* growth and survival for these 31 sites are compared, with results comparable to that reported for Palau.

THE population of giant clams (family Tridacnidae) in the Indo-West Pacific is in a state of decline due to the combined effects of pollution, environmental degradation, as well as harvesting for commercial and subsistence purposes (Munro 1983). The giant clam *Tridacna gigas* once flourished in Yap. Now only an occasional shell is found at dredge sites. Other species of tridacnid clams are present, but according to local residents, their populations are much reduced.

In Palau, the chief reason for the decline of clam stocks is illegal harvesting, primarily by Asian fishing vessels (Heslinga and Perron 1983). In 1983, Taiwan imported 200–300 t of giant clam adductor muscle annually worth US$20–25 million retail. Illegal harvest is not documented in Yap, but may occur.

As a result of spawning and rearing techniques recently developed by the Micronesian Mariculture Demonstration Center (MMDC) in Palau, seed clams are now available in abundance. As a result of declining local stocks, and the recent technological breakthroughs by MMDC, Yap State initiated this clam reseeding project to reestablish tridacnid clams in Yap.

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Methods

Fifteen-month-old post-fertilisation *Tridacna derasa* clams were ordered from MMDC in Palau. The clams were purchased by Yap State Legislature at an initial cost of US$1320 for clams and protective grow-out trays. A shipment of 1014 was delivered to Yap State by air on 26 January 1984.

Arringel, Delipebinaw was selected as the original grow-out site. It was screened for predators such as octopus, hermit crabs and predatory snails. The site was chosen to be the nursery site for the juvenile clams because it met the specific requirements suggested by Heslinga et al. (1984 a,b):

(1) well sheltered, but excellent tidal flushing;
(2) minimum of 1.5 m at low tide, and maximum depth of 3–4 m;
(3) oceanic salinity at 32–34 ppt;
(4) temperature of 26–31°C;
(5) coarse sand or coral rubble bottom with live coral present;
(6) minimum of freshwater inlets; and
(7) absence of predators.

Upon arrival, the clams were placed on gravel substrate in fiberglass grow-out trays (60 × 60 × 5 cm). Mesh covers of 2.5 cm polyethylene were employed as clams smaller than 10–15 cm experience high mortality from fish predators if unprotected (Heslinga et al. 1984).

Twenty grow-out trays were used. Each tray was stocked with 50 clams/tray for a density of 138

clams/m^2. One tray was stocked with 64 clams. Twice weekly check of clams for removal of predatory snails and thinning is recommended (Heslinga 1985). Clams were checked weekly.

After 3 months in Yap (March 1984), the 18-month-old clams were transplanted to four sites around Yap Proper for growth and survival comparisons. These sites were: Ngof, Rull; Arringel, Delipebinaw; Chool, Maap; and Wanyan, Gagil.

Approximately 200 clams were removed to each of three sites. Eight trays of clams (approximately 400 clams) remained at Arringel. At the Arringel site, clams were relocated a short distance (< 100 m) to minimise predation mortality.

The clams were then checked monthly. In June 1984, the clams were thinned to a density of 25 clams/tray (69 clams/m^2). Twenty additional trays were added to accommodate clams. The clams remained at the four sites in trays from April 1984 to January 1986.

In January 1986, the clams were distributed in groups of about 20 to inshore areas of 28 villages of Yap. Since the clams were over 2 years old and 15 cm shell length, they were placed unprotected on the reef. Survival of 90% may be expected for clams of this size (Heslinga et al. 1985).

After the January 1986 distribution, clam measurements and counts were made at each site (April 1986). Clams were measured underwater using scuba gear. Shell length was recorded on waterproof sheets.

Three additional sites were seeded with clams between February and September 1986. These sites were Ngariy, Bulwol and Ganaun.

In September 1986, another clam count and measurement was completed. The measurements were taken by scuba divers of MRMD staff. Clams were placed on plastic data sheets and their shell length recorded.

Results

In the first month in Yap (January 1984), clams experienced no mortalities. In February through July 1984 the mortality rate was high (Table 1).

Clam survival between January 1984 and September 1986 was 59.1% (Table 1). In the December 1985 survey, two trays (40 clams) were missing from the Chool site. In the September 1986 survey, the Tawoway and Malaay sites could not be located. The 40 clams from these sites are considered 'missing.'

The highest survival between the sites from March 1984 to March 1985 was recorded at Ngof with 84%.

Over half of the sites experienced no mortalities between April and September 1986. At the Adubuwee site, two clams were taken to the outer islands in experimental shipping trials in mid 1986.

TABLE 1. Survival and growth of 1014 18-month-old clams over 33 months in Yap Proper.

Age (months)	Year/month (date)	No. clams	Survival (%)	Average size (cm)
15	1984 Jan	1014	100.0	8.4 (100)[a]
16	Feb	1010	99.6	
17	Mar	980	96.6	9.9 (200)
18	Apr	944	93.0	
19	May	897	88.5	
20	Jun	855	84.3	
21	Jul	839	82.7	11.9 (200)
22	Aug	817	80.5	
23	Sep	807	79.6	
24	Oct	803	79.2	
25	Nov	782	77.1	
26	Dec	775	76.4	14.4 (80)
27	1985 Jan	775	76.4	
28	Feb	756	74.5	
29	Mar	752	74.2	
30	Apr	740	72.9	
32	Jun	733	72.3	
33	Jul	719	70.9	
36	Oct	715	70.5	
42	1986 Apr	659[b]	64.9	19.5 (659)
47	Sep	599[c,d]	59.1	21.6 (599)

[a] Quantity of clams measured indicated in parentheses.
[b] 40 clams missing from Chool, Maap.
[c] 40 clams missing in Tawoway and Malaay.
[d] Two clams taken to outer islands.

The Ngariy, Bulwol and Ganaun sites were seeded after the April 1986 count and measurement work. Thus survival rates between April and September 1986 for these sites cannot be calculated. Clams for these sites originated in Ngof, Wanyan and Arringel, and clam survival for these original sites is therefore low.

The Bechyal site experienced 105% survival, suggesting that one additional clam was placed there between April and September 1986.

Clam growth rate was documented (Table 1). The 1014 clams received in Yap (January 1984) had a mean shell length of 8.41 cm (SD = ± 0.83, n = 100). Three months later (March 1984), the mean size of the clams was 9.96 cm (SD = ± 0.91; n = 200).

The average growth rates of the clams from January 1984 to September 1986 was 6.3 cm/year for 18–30-month-old clams (year 1 in Yap) and 3.8 cm/year for 30–42-month-old clams (year 2 in Yap).

Discussion

Fifteen-month-old *T. derasa* have been reared successfully in Yap Proper for 33 months. Grow-out was conducted in ocean-nursery, shallow-lagoon areas around Yap Proper. Procedures developed in

Palau by MMDC have been transferred to Yap with positive results.

Mortalities from age 17 to 21 months were very high. Survival was 85.6% between these 4 months, possibly due to inadequate monitoring of clams. A significant cause of mortality came from the carnivorous snails *Cymatium muricinum* and *Chicoreus ramosus*. According to Heslinga (1985), these snails are responsible for 75–85% of the mortalities of ocean-nursery phase juvenile clams.

Wanyan and Ngof appear to be the best sites for seeding clams around Yap Proper. After 11 months, these sites experienced 80.6 and 83.9% survival respectively. Missing clams at Chool resulted in a low survival rate there, while Arringel had 71.2% survival during the same period.

After transplanting to villages (January–February 1986), clam survival was 100% for over half of the 29 sites. This zero mortality may be due to the age (2 years post-fertilisation), and size (15 cm) of clams transplanted. At this size the clams should enter male phase sexuality and should no longer be susceptible to common predators. The muricid snail *Chicoreus ramosus* which can kill clams up to 30 cm (Heslinga et al. 1984) may still be a problem.

Growth comparisons cannot be made between the four sites due to insufficient data for April 1984 through February 1986. Clam growth appears comparable, if not slightly better than that reported by Heslinga et al. (1984).

Generally, the average growth rate in Palau is 5 cm/year for the first 5 years (Heslinga 1985). The average growth rate for the 4-year-old clams in Yap is 5 cm/year.

The growth rates in relation to the village sites in Yap indicate the Yyin and Meechol sites are the most favourable for clam seeding in the future. Places with poor growth and survival are Chool and Woned in Maap, and Lebnaw and Gachpar in Gagil.

Overall, sites with favourable survival and growth rates include Yinuf, Nef, and Yabach in the southern end of the island, and Riy, Meechol, and Yyin in the northwestern locations. Survival and growth is comparable to trial studies in Palau (Heslinga 1985).

Status of Giant Clams in Indonesia

Bonar P. Pasaribu*

Abstract

Giant clams have been utilised for the tile industry in Indonesia since the 1960s. Although the clams have been widely known throughout Indonesian coastal waters, studies on clams are still limited to inventory work. The utilisation of clams is increasing and the clam production is gradually decreasing. In the northern coast of Java Island, the exploitation of clam fossils has damaged the living corals. The Government of Indonesia has declared the giant clams protected species.

GIANT CLAMS are found in Indonesian coastal waters. There are five species of *Tridacna* and two species of *Hippopus*, and the stocks are gradually decreasing because of intensive exploitation by fishermen and the rising demands of local markets. The utilisation of giant clams has been under way for nearly three decades, being traded for their meat and shells. The clam shells are now used as materials for the tile industry.

Research and development for clam species are still in the stages of preparing stock inventories which have not yet been completed throughout the country. The clam research work was only carried out in Seribu islands and Karimun Jawa islands, in northern Java. It is hoped that more progress can be made in future by increasing the number of survey sites and through more detailed study of the clams.

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Species Distribution

In Indonesia, the following species are found: *Tridacna gigas, T. derasa, T. squamosa, T. crocea, T. maxima, Hippopus hippopus* and *H. porcellanus*. Distribution and habitat of these clams are shown in Table 1 (Romimohtarto et al. 1987).

TABLE 1. Distribution and habitat of Indonesian giant clams.

Species	Habitat	Distribution area
T. gigas	Living coral rock and coral beach	All Indonesian coastal waters
T. derasa	Living coral rock and coral beach	All Indonesian coastal waters except Northern Sumatera Island
T. squamosa	Coral rock, strongly tied to coral stone with thin thread	All Indonesian coastal waters
T. crocea	Buried or tied to massive coral with mantle showing	Coastal waters of Sumatera, Jawa, Kalimantan, Sulawesi, Irian Jaya, Bali, Western and Eastern Nusa Tenggara islands, and other small islands
T. maxima	Coral rock sand, and between living corals	All Indonesian waters
H. hippopus	Sandy coral rock, generally not tied to substratum	All Indonesian waters
H. porcellanus	Sandy coral rock, generally not tied to substratum	All Indonesian waters

Formerly abundant throughout Indonesia, three species (*T. gigas, T. derasa* and *H. porcellanus*) have now decreased markedly. Usher (1984) stated that *T. gigas* has been eliminated from western Indonesia.

Observations on coral destruction by exploring giant clam fossils were carried out in the Karimun Jawa islands (Sya'rani 1987). The living corals are badly damaged, and the living coral cover is less than 5%.

Utilisation

Giant clams are exploited as a cash crop by coastal people. The tasty clam meat is used as a food resource, and its shell is utilised traditionally for a variety of purposes such as ornaments, ashtrays, washbasins, etc., and now for the tile industry, which started in the early 1960s centred at Jakarta. Then in the mid 1970s, it spread out to Jepara, Central Java Province. The clam production entered Jakarta from Seribu islands, in the southern part of Sumatera Island and western Java Island. Clam production for Jepara comes from the northern coast of central Java and east Java provinces, and from Karimun Jawa islands.

Fossil clam shells for the tile industry are taken by the fishermen who use a 1–2 m iron bar and search for the fossils about 1 m below the surface of the sand. Fishermen use traditional small wooden boats (up to 3 m) and some of the fishermen are equipped with snorkel equipment. Women do not participate when searching and taking clams from the sea. However, women are involved in the processing of clams.

Clam meat is usually dried and it is sold in local markets at about US$1.50/kg. The meat consumption is limited to the people who live on the coast, most of them in the northern part of Java Island.

The clam shell trade in Jakarta was 7920 t in 1982 (Usher 1984), decreased to 3677 t in 1984 according to Conservation of Natural Resources Institute (1986), and dropped sharply to 260 t in 1985. In Jepara, the clam shell production also gradually decreased. However, in the same period the value of clam shells increased (Sya'rani 1987) — i.e. 2000 t in 1982 to 1750 t in 1985 with a price of US$0.04/kg to US$0.07/kg, respectively. There are no available data indicating the clam production and its value in areas other than Jakarta, West Java Province and Central Java Province, although clams are exploited in the other provinces.

The marketing chain of clam shells is through two collecting merchants before reaching the tile industry. The shell production in Jakarta is sold in the Jakarta area only, while the production in Jepara is distributed to several markets in Central Java (i.e. Kudus, Semarang, Tegal, Solo and Yogyakarta).

The price of clam shells sold by fishermen to collecting merchants, is based on three criteria: (1) Dissected clams consist of 10% 'skin' and 90% shell products, with the price of US$0.05/kg; (2) Half dissected clams containing 25% skin and 75% shell products, are US$0.04/kg; and (3) Clams without dissection consist of 40% skin and 60% shell, and are sold at US$0.03/kg.

The collecting merchants process the clam shells into pieces in Jepara and sell them between US$0.06 to US$0.07/kg in Central Java markets. In Jakarta, the processing of shells is also made into smaller pieces and ash. The prices of these pieces range from US$0.07/kg for code 0.1 to US$0.03/kg for code 0.6, and the ash sells for US$0.012/kg.

The clam shell industry is fairly intensive both in Jakarta and Jepara. Small boats (~12 m) are used for transporting the shells to South Sumatera and Seribu islands to Jakarta, as well as from Karimun Jawa islands to Jepara.

The trade of clam meat and shells is mostly domestic. There have been no foreign fishing boats detected in Indonesian coastal waters exploiting the clams illegally, and so far the government does not issue licences for legal utilisation of Indonesian clams for foreign fishing boats.

Research and Development

Studies on giant clams are carried out only in Seribu islands, Karimun Jawa islands and some coastal areas of northern Java Island. There are no intensive studies being carried out on clams in the other areas of Indonesia.

Panggabean (1987) estimated the standing stock and carried out preliminary culture of clams in the Pari Reef area, Seribu islands. In this study, the transects and aerial surveys were used to provide standing stock estimation of tridacnid clams. The results show the following populations: *T. gigas* and *T. deresa*, zero; *T. crocea*, 21500; *H. hippopus*, 6100; *T. squamosa*, 1200, and *T. maxima*, 1200. Preliminary culture studies using *T. squamosa* have been done in a new concrete raceway and were not successful. The 16 mature clams put into the tank died, probably because of toxic substances released by the new cement.

Sya'rani (1987) observed the effects on living coral cover in the exploitation of the giant clam fossils area at Karimun Jawa islands. His observations reveal that the exploitation of clam fossils badly damaged the living corals. The recovery takes years, because turbidity is high and sea-grass dominates certain areas, creating unfavourable conditions for coral growth.

The protection of 15 species of marine

invertebrates has been declared by the Government of Indonesia through the Minister of Forestry, in his decree dated 12 January 1987. There are also 13 marine reserves which have been declared by the government. Seribu islands and Karimun Jawa islands are among five marine reserves proposed as Marine National Parks (Atmawidjaja 1987).

The intensive research work and culture of clams in Indo-Pacific areas could overcome the decrease in clam populations or even the disappearance of clams in certain areas, and would be a great contribution to the clam industry. It is also hoped that Indonesia will do more research and development on giant clams in future.

Legal protection excludes human intervention in theory, but in the absence of adequate and appropriate controls, the protection would be of little value. The Jakarta area is an exception, where routine observations are carried out by the staff of the Directorate General of Forest Protection and Nature Conservation of the Department of Forestry, in conjunction with the police and municipal authorities. Such vigilance led to the confiscation of 15 clam shells and the prosecution of the offenders (Atmawidjaja 1987). However, in other areas, observations are rarely done because of lack of nature conservation staff.

Conclusions

(1) The utilisation of giant clams is increasing, and clam populations are decreasing. Although the availability of clam shells is decreasing, the price is increasing.
(2) The exploitation of clam fossils has badly damaged the living corals.
(3) Research work on giant clams in Indonesia is still in the inventory stage. Attempts at preliminary culture have so far been unsuccessful.
(4) Protection of giant clams has been declared by decree of the Government of Indonesia. However, lack of staff prevents the full implementation of the legislation.

Status of Giant Clams in Kiribati

T. Taniera*

Abstract

Four species of Tridacnidae are found in Kiribati: *Tridacna maxima, T. squamosa, T. gigas* and *H. hippopus*. Because of heavy pressure on existing populations of giant clams for local use, commercial exploitation will require the development of a hatchery for reseeding, and studies on the market potential.

As a result of Munro's (1986) survey, four clam species have been identified from Kiribati islands: te were (*Tridacna maxima*), te were matai (*T. squamosa*), te neitoro (*Hippopus hippopus*), and te kima (*T. gigas*).

There is a possibility that other species may exist off islands not yet surveyed. The fishermen think there are only three species: *Tridacna squamosa* does not appear in their list.

Tridacna gigas is absent in the Line and Phoenix group (Rosewater 1965) and *H. hippopus* is found on sand or rubble areas and not directly on the reef. The others are confined to shallow sunlit waters from intertidal reef crests or flats to depths of around 15 m, of which *T. maxima* is the most widely distributed species. The fishermen do not differentiate between *T. maxima* and *T. squamosa* and when fishing these two are classified as te were (*T. maxima*).

Use of Clams

Traditionally every I-Kiribati male is taught how to cut toddy and fish for we depend entirely on fish and coconut. It was believed that there was an adequate supply of fish and it was only consumed as a subsistence food. There was no selling of fish, because every family is always supplied with fish. The barter system known as *te kaonono* is a practice where fish can be exchanged for other goods. *Tridacna gigas* and *H. hippopus* are 'cultured' for food and 'pets.' Male members of a family collect small giant clams and culture them in nearby shallow water until they are prepared for the feast. These species could be either *T. gigas* or *H. hippopus*. *Hippopus hippopus* is the most appropriate one since it does not grow as big as *T. gigas*.

Tridacna maxima empty shells were and are used for mashing leaves for local medicines, whereas *T. gigas* empty shells are used for crushing *te karababa*, preserved traditional food made out of pandanus fruit, as troughs for feeding pigs and as tubs.

Traditional Beliefs

There is a belief that, when *T. gigas* has reached its maximum size, the entire flesh will burst out and turn into a skate fish (ray fish), and this may be the reason why giant clams are quickly exploited while they are still immature!

Preservation

If there is an adequate supply of four clam species these are usually salted and stored for later use when the fish supplies are scarce. The salted product has to be supersaturated otherwise it will be wasted if only a small amount of salt is used. For local markets these are stored in barrels and shipped to South Tarawa, the capital. The clams are occasionally sun-dried after rinsing them in water (no salt is added). A modern preservation method these days is to marinate the *T. maxima* in a small amount of vinegar mixed with sour toddy (fermented sap obtained from sheaths of coconut palms).

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Cooking

The entire meat is eaten raw or boiled, sometimes cooked in coconut cream if there is a small quantity of meat. Traditionally these were baked in fresh coconut sheaths in the Kiribati oven (made in the ground which is dug to about 50 cm deep and then the stones are placed on top of the firewood, covered by old mats or sacks). When cooking the salted product these are first soaked in seawater for about half an hour then rinsed thoroughly with water before they are cooked. This reduces the salt content in the clam or other salted product like fish, etc.

Reef Ownership and Women's Role

Unlike land, the reef is not owned by anybody (except *te maa* — customary fishing trap) and therefore people can fish anywhere apart from *te maa*. The women are involved in cooking the clams which are substitutes for protein when fish supplies are scarce, and sometimes are involved in collecting *H. hippopus* on the reef.

Fishing

Fishermen use a bush knife for *T. gigas*, and a sharpened table knife for the other species. The adductor muscle is pierced to open the shell. The meat is then scraped out of the mantle of *T. gigas* by hand, and knives are used to do this for the other three species. Some people throw large stones into the clam shell or use an oar to force open the shell before piercing the adductor muscle. The smaller *T. gigas* are sometimes lifted onto the canoe where the meat is extracted.

Current Domestic and Export Trade

Tridacna maxima, the most widely distributed, is believed to be overexploited and is mainly used for local markets and sold fresh or salted on outer islands. The salted and marinated (in sour toddy) products are currently sold on South Tarawa in private shops and the prices will surely increase in the future.

No formal fisheries infrastructure exists in Kiribati either for research or development programs.

Conclusion

Munro's (1986) report indicated that commercial fishing should not be entertained because the subsistence consumption alone is putting heavy pressure on the resource.

Our future requirements are to develop a hatchery for reseeding and to investigate the market potentials.

Giant Clam Research and Development in Palau

G.A. Heslinga, T.C. Watson and T. Isamu*

Abstract

The Micronesian Mariculture Demonstration Center has successfully developed a low-cost, low-technology system for giant clam spawning, culture, and grow-out in shallow coral reef waters. The Center has cultured all seven tridacnid species, and has found that *Tridacna derasa* combines the best biological attributes for farming. The current program priorities for the Center are discussed.

GIANT tridacnid clams were historically an important seafood in the Indo-Pacific region, but in many areas natural stocks have been reduced to biological or economic extinction by subsistence and commercial harvesting. During the past 5 years the Pacific Fisheries Development Foundation (NMFS/NOAA), the U.S. Department of the Interior, FAO and other international agencies have funded a giant clam research and development program based at the MMDC laboratory in the Republic of Palau.

The MMDC has pioneered the development of a low-cost, low-technology system for giant clam spawning, larval culture, juvenile culture, and grow-out in shallow coral reef waters. Clam growth rates under cultivation have been shown to be relatively rapid, even in the absence of food or fertiliser inputs. Techniques have been developed for control of pests, predators and algal fouling. A direct-drive diesel seawater pumping system has been installed, eliminating dependence on municipal power grids.

MMDC personnel have cultured all of the seven tridacnid species, producing over one million seed clams and some 31700 kg of biomass. Of the seven species examined in Palau, *Tridacna derasa* combines the best biological attributes for farming. Several cohorts have been raised to full sexual maturity at 5 years of age, and production of second-generation cohorts is now practiced routinely, giving independence from wildstocks and making selective breeding possible. Techniques have been developed for air-freighting seed clams abroad, and so far nearly 50 international shipments have been made. In 1987, revenues from sales of seed clams at the MMDC were used to expand the hatchery, doubling its size and production capacity. A further doubling in hatchery size will be undertaken in 1988–89 with grant financing from USDA/CTSA.

Low-technology methods for giant clam hatchery culture and grow-out are now being transferred, with demonstrable success, to a number of other countries in the region. Some 12 nations or nation-states in the tropical Pacific have undertaken personnel training and stock enhancement programs using seed clams produced and marketed by the MMDC. Ocean-based cultivation of giant clams is proving to be technically and socially feasible in some very remote Pacific island settings, where other kinds of marine and terrestrial farming are clearly impractical. For example Yap State (FSM) has implemented a village clam production program, enabling more than 40 municipalities to initiate subtidal giant clam gardens using seed from Palau.

The MMDC's mariculture training and extension efforts have been formalised into a practical, 30-day short course. The course is offered on a continuous basis throughout the year and features hands-on experience with all aspects of clam culture, from spawning and larval rearing to ocean culture and broodstock management.

The MMDC has completed implementation of an on-site quarantine facility for treatment of shipments of seed clams destined for export to Pacific island countries. This is in response to South

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Pacific Commission recommendations and to popular demand. The quarantine procedure follows specifications in use at James Cook University in Australia, and includes holding specimens in 1μm filtered, ultraviolet-sterilised seawater for a minimum of 1 month before export. All specimens are manually scrubbed and washed in chlorinated fresh water prior to quarantining.

In 1987-88 the MMDC began marketing 1- and 2-year-old *T. derasa* as aquarium specimens. Exports from the MMDC hatchery are routed to Honolulu, then to the U.S. mainland and Europe (England and West Germany). The potential size of this market is not known but the current demand exceeds the MMDC's available supply. Opportunities exist for other hatcheries in the region to begin supplying aquarium markets.

Current program priorities for which the MMDC has secured funding include: (1) expansion of tridacnid hatchery production facilities; (2) doubling of enrollment in the Clam Mariculture Training Course; (3) establishment of 30 new subtidal clam nurseries in the U.S.-affiliated Pacific islands during the next 2 years; (4) continuation of applied research on nutrient enhancement, selective breeding and symbiosis; (5) exploration of new markets for clams and clam products; (6) collaborative research on production economics; and (7) production of a manual and video on low-technology clam culture.

Giant Clams in the Philippines

E.D. Gomez* and A.C. Alcala**

Abstract

All seven known species of giant clams occur in the Philippines. However, only the smaller, attached species *Tridacna crocea*, *T. maxima*, and *T. squamosa* are widely distributed. Of the four unattached forms, only *Hippopus hippopus* occurs in some numbers while the other three, *H. porcellanus*, *T. derasa*, and *T. gigas*, are virtually extinct from most of the country due to overexploitation.

Both shell and meat are utilised, with the former being a more important commodity. All species are harvested with women playing an equally important role as the men. The clams are harvested from reef areas which are common property, without any management program at present.

Research on giant clams in the country is undertaken principally by two institutions: Silliman University Marine Laboratory and the University of the Philippines Marine Science Institute, with funding from the Australian Centre for International Agricultural Research and to a more limited extent with support from the Philippines Council for Aquatic and Marine Research and Development. Studies have included resource surveys, growth, and mariculture.

THE Philippine archipelago of some 7000 islands is located in the species-rich marine realm called the Indo-West Pacific. Since many species of marine organisms have their highest diversity in this region, it is not surprising that all seven known species of giant clams (Tridacnidae) are found in the Philippines. These are *Tridacna crocea*, *T. maxima*, *T. squamosa*, *T. derasa*, *T. gigas*, *Hippopus hippopus*, and *H. porcellanus*. It is interesting to note that the existence of the last species had been known for a long time by shell dealers who named it the 'China clam,' but its separate identity as a true species was not recognised until Rosewater (1982) described it. As late as 1983, Munro referred to only six living species. More recently, evidence is being sought in Fiji for a possible eighth species.

This paper attempts to summarise the knowledge on the distribution and abundance of giant clams in the Philippines as well as to indicate the utilisation of the species. A small section is also devoted to research.

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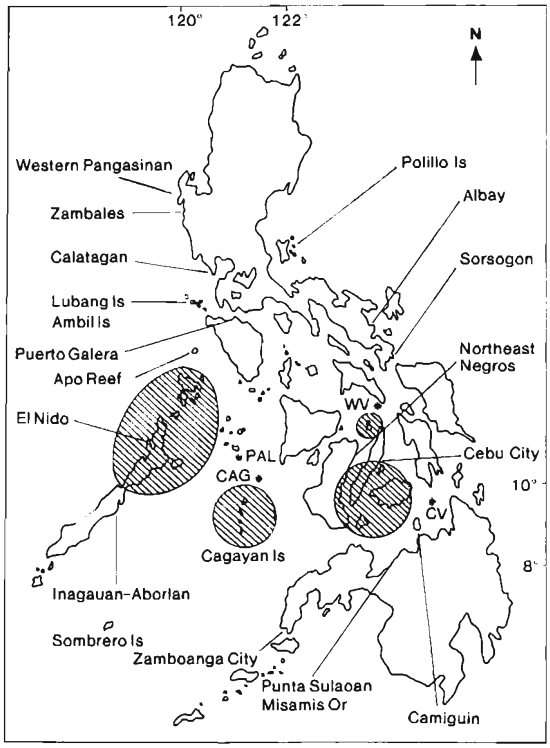
Distribution and Abundance

The distribution and abundance of giant clams in the Philippines have been the subject of technical reports of the ACIAR-funded project and of several papers (Alcala 1986; Juinio et al. 1988 a, b), so much of the detail will be omitted here. Some 250 sites in more than 20 localities, mostly in northern and central Philippines, were surveyed. Data are therefore sparse for the eastern, southern, and western sectors of the country. The general locations of the survey sites are indicated in Fig. 1. From the results of the surveys conducted by both of our institutions a composite summary table was prepared (Table 1).

The results indicate that the most abundant species are the three attached, smaller species, *Tridacna crocea*, *T. maxima* and *T. squamosa*. While some horsehoof clams (*H. hippopus*) are sometimes found in not insignificant numbers, these are not common. The remaining three species, *T. derasa*, *T.gigas*, and the China clam (*H. porcellanus*), are virtually extinct in the country.

Most of the clams observed were encountered in depths of < 10 m, no doubt because of their dependence on light for their symbiotic algae.



Population densities were generally low because of the fishing pressure. In more remote areas such as Polillo Island on the Pacific side of Luzon and in some of the islands of the Sulu Sea, there were some areas that gave densities of clam from 126 to more than 3500/ha. More often than not, however, densities were an order of magnitude smaller.

Some of the clams found during the field surveys were well hidden in thickets of the staghorn coral *Acropora*. By thus being shielded from the view of free-diving fishermen, they escaped collection.

Utilisation

A summary article on the use of giant clams in the country was prepared by Juinio et al. (1987).

Many Filipinos have their first encounter with giant clam products in churches where they are commonly used as baptismal or holy water fonts (hence, the French name 'benitier'). Although the shells are now less common in churches, they are becoming more popular as soap dishes, salad bowls,

Fig. 1. Location in the Philippines of the different areas covered by the field surveys. Shaded areas are those surveyed by the Silliman University Laboratory (WV, Western Visayas; CV, Central Visayas; CAG, Cagayan Island, Palawan; PAL, Palawan).

TABLE 1. Summary of population densities in each locality surveyed by the UP Marine Science Institute and Silliman University Marine Laboratory (*) for *T. crocea* (Tc), *T. maxima* (Tm), *T. squamosa* (Ts), *T. derasa* (Td), *T. gigas* (Tg), *H. hippopus* (Hh) and *H. porcellanus* (Hp).

Locality	No. of sites	Area surveyed	No. of clams	Density (clams/ha)							
				Tc	Tm	Ts	Td	Tg	Hh	Hp	All sp.
Luzon											
W Pangasinan	15	5.30	62	7.4	1.1	3.2	0.0	0.0	0.0	0.0	11.7
Polillo, Quezon	20	2.10	7410	3399.0	53.3	70.0	2.9	1.0	2.4	0.0	3528.6
Zambales	8	1.04	27	18.3	6.7	1.0	0.0	0.0	0.0	0.0	26.0
Albay	15	1.45	281	82.1	70.3	41.4	0.0	0.0	0.0	0.0	193.8
Sorsogon	7	1.48	171	31.1	81.8	2.7	0.0	0.0	0.0	0.0	115.5
Calatagan	10	1.11	55	12.6	10.8	26.1	0.0	0.0	0.0	0.0	49.5
Lubang	9	1.49	127	56.4	14.8	13.4	0.0	0.0	0.7	0.0	85.2
Ambil	16	2.50	273	26.8	44.8	82.0	9.0	1.0	2.0	0.0	109.2
Apo Reef	15	0.88	111	29.5	94.3	1.1	1.1	0.0	0.0	0.0	126.1
Puerto Galera	13	1.46	32	2.7	9.6	9.6	0.0	0.0	0.0	0.0	21.9
Visayas											
NE Negros	4	0.29	4	6.9	3.4	3.4	0.0	0.0	0.0	0.0	13.8
Central Visayas*	25	3.00	93	16.3	8.0	6.7	0.0	0.0	0.0	0.0	31.0
W Visayas*	8	0.70	129	22.9	30.0	131.4	0.0	0.0	0.0	0.0	184.3
Palawan											
El Nido	22	2.55	428	109.8	9.0	49.0	4.7	0.0	4.7	0.4	172.9
Inagauan-Aborlan	5	0.45	5	0.0	6.7	2.2	2.2	0.0	0.0	0.0	11.1
Sombrero Is	2	0.20	66	250.0	65.0	10.0	5.0	0.0	0.0	0.0	330.0
Cagayan Is	10	0.64	209	51.6	260.9	4.7	0.0	1.6	7.8	0.0	326.6
Cagayan*	10	0.56	253	180.7	255.1	12.4	0.0	0.0	0.0	0.0	448.2
Palawan*	21	2.10	7051	3286.2	26.7	27.1	3.8	0.0	13.8	0.0	3357.6
Mindanao											
Camiguin Is	10	2.13	123	11.3	31.0	15.5	0.0	0.0	0.0	0.0	57.8
Punta Sulaoan	2	0.15	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

and ashtrays. Indeed, the uses of entire giant clam shells are varied, particularly for ornamental purposes. More recently the shells have been fragmented or cut up for diverse uses as necklaces and table inlays in the shellcraft industry.

The popularity of shells was such that before the inclusion of the tridacnids in CITES, there was a large export from the Philippines. No doubt some are still being smuggled out of the country.

Giant clam meat is a supplementary food item in coastal towns in the country. It is not usually a regular item for sale in markets. Its actual consumption is greater as many fishermen gather it for personal or home use.

Clam meat in the Central Visayas is usually eaten raw as 'kinilaw,' although occasionally it is cooked in coconut oil. In the past, *T. gigas* meat was sun-dried after which it was broiled. In the Visayas at present, the *Tridacna* species are preferred; *Hippopus* is considered less palatable. Because of their rarity, giant clams do not constitute a significant source of protein in the Central and Western Visayas. In the latter region, they are rather a secondary source, being gathered only if fish is not available. This situation may change if tridacnids are farmed and readily available in the market. Some clam meat was exported prior to the CITES prohibition. Noteworthy was the export in 1984 of 1000 kg of *T. crocea* frozen meat from Polillo Island. With the present prohibition, any exportation would be done illegally offshore involving foreign carriers.

Fishery

Giant clams are gathered from reef flats during low tides by women and children. From the deeper subtidal areas, men gather whole specimens of the smaller species by free-diving. In the past, free divers (and poachers) sometimes removed only the flesh, leaving the valves at the sea bottom. This explains the presence of litter of valves of the larger species and the large individuals of smaller species at the sea bottom in the Sulu Sea. However, in recent years, large valves fetched good prices and were therefore collected for commerce.

There is no distinctive role of women in the giant clam fishery aside from their collecting activities in the intertidal zones at low tides. They actively participate in the processing of clam shells for ornamental purposes in the shellcraft industry. As a matter of fact, they probably do most of the lighter work such as stringing necklaces with clam shell discs.

In the context of the national fishing effort, the giant clams now contribute a small production because of the dwindling resources. Unlike the situation that may prevail in some of the small island countries in the South Pacific, clams are not a major fishery commodity in the Philippines which is a large fishing country with a total fishery production of more than 1.25 million t/annum.

Reef Ownership

Reefs are considered common property in the Philippines. There is, however, a move on the part of some local communities, particularly with the support of development agencies, to manage reef resources. Under this scheme, a coastal family would be given a stewardship contract to use for seafarming and/or sea ranching a small area of reef for a specific period of time. It is believed by development agencies that such a scheme is an alternative to the present open-access policy, which has been blamed for the degradation of marine environments and resources.

Research

Giant clam research in the country was virtually nonexistent before the inception of the ACIAR-funded project. It should be noted that the original proposals from the Philippines were packaged by the International Center for Living Aquatic Resources Management (ICLARM) in the context of the International Giant Clam Program. ACIAR was the first funding institution to give significant international support for giant clam research. In the Philippines, local counterpart funding has been provided by the Philippine Council for Agriculture and Resources Research and Development (PCARRD) and more recently by one of its offshoots, the Philippine Council for Aquatic and Marine Research and Development (PCAMRD).

In terms of activities, the two Philippine institutions have collaborated and coordinated with each other. Thus, in the resource survey, the country was divided geographically. For both the mariculture and growth studies, materials have been shared or exchanged for mutual benefit. Differences lie in the habitats that have been utilised for the ocean nurseries and some of the types of experiments and activities that have been carried out. Details of some of these will be elaborated in the technical presentations of research results by the various research staff of the two institutions.

Acknowledgments

The research activities of the two institutions were made possible through funding from ACIAR Project No. 8332 coordinated by James Cook University. Thanks are also due to the various research personnel of the project based at Silliman University and the University of the Philippines.

Giant Clam Resource Investigations in Solomon Islands

Hugh Govan*, Paul V. Nichols and Hugo Tafea****

Abstract

Six species of tridacnid clam have been found in Solomon Islands: *Tridacna gigas, T. derasa, T. squamosa, T. maxima, T. crocea*, and *Hippopus hippopus*. These clams are an important food source in many coastal areas and the shells are used to some extent in the local carving and jewellery trades. The legal trade in clam products is of insignificant commercial value, nevertheless, large numbers of tridacnids have been harvested, particularly by Taiwanese fishermen, and stocks of the larger species are severely depleted in some areas.

SOLOMON ISLANDS comprises some 800 islands with a land area of about 28 000 km^2, extending over 1400 km in the western equatorial Pacific Ocean. The islands are located in two archipelagoes (Main Group Archipelago or MGA and Temotu) between latitudes 5° and 13°S and longitudes 155° and 168°E.

Solomon Islands is one of the few countries in the region with relatively good stocks of all species of tridacnid clams (with the probable exception of *Hippopus porcellanus*). There is also a great diversity of coastal marine habitats, ranging from deep fjords to atolls and from coastal shelves to immense lagoon systems.

In its current National Development Plan, 1985–89, the Solomon Islands Government (SIG) has as one of its prime development objectives the attainment of increased income-earning possibilities for SI nationals in the rural fisheries sector, as well as increased participation in fisheries-related enterprises, including aquaculture (SIG 1985). Socioeconomically beneficial development projects involving the culture of appropriate organisms are seen as a priority in the development aspirations for the fisheries sector in this country. Due to the wealth of relatively underexploited marine resources, emphasis is being placed only on organisms with high cash-earning potential, e.g. prawns, seaweeds, and clams.

With this aim in view, SIG in conjunction with the Guadalcanal Provincial Assembly invited the International Center for Living Aquatic Resources Management (ICLARM) in 1986 to establish a Coastal Aquaculture Centre (CAC) on the north coast of Guadalcanal, some 25 km to the west of the nation's capital, Honiara. As the initial research thrust, the CAC aims to develop low-cost methods of propagating and cultivating tridacnid clams, principally *Tridacna gigas*, in a collaborative research and development project executed by ICLARM and the Fisheries Department of the Ministry of Natural Resources, SIG. As the CAC develops, expansion of research into the development of appropriate methods for culturing other suitable organisms will be considered. The CAC also serves as the seat of ICLARM's South Pacific office. The establishment of the CAC is considered as a major support to SIG's aspirations to develop Solomon Islands' fledgling aquaculture industry. The work programs of the CAC are in line with SIG national priorities for fisheries development, and it is anticipated that the CAC's work will have regional application to members of the South Pacific Forum in years to come.

During the period of establishment of the CAC, investigations have been made into Solomon Islands' tridacnid resources and this paper is based on field trips undertaken by CAC staff to some areas

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(New Georgia, east and west Guadalcanal, north and south Malaita, Ysabel, and Savo) and on reliable reports made by Fisheries Department staff and local fishermen. On none of the field trips were quantitative surveys carried out, but presence or absence of different species was ascertained as was their relative abundance.

Species Distribution

Tridacna gigas

Distribution *Tridacna gigas* seems to be found throughout the MGA but is generally rare in areas of high population density and fishing pressure such as the north coast of Guadalcanal and northwest Malaita. *Tridacna gigas* has been observed in southern Malaita, eastern Guadalcanal, Ysabel, and eastern New Georgia. The species is reliably reported from Choiseul, Gela, Wagina, Shortlands, Sikaiana, western New Georgia, and the Russell Islands. It is also reputed to be present in Rennell, Ontong Java, and Temotu.

Habitat This species is found on coral rubble and embedded in living coral, on all types of reefs, between the intertidal zone and depths to 15 m. In the Marau Sound and the Marovo Lagoon, *T. gigas* appears to be more abundant on the outer reefs than in the lagoon interior. The reasons for this are unclear.

Tridacna derasa

Distribution *Tridacna derasa* appears to have the most restricted distribution of all tridacnid species within Solomon Islands. To date this species has only been observed in the Marau Sound and the northern Marovo Lagoon although it is reputedly present in other areas.

Habitat Not enough specimens have been observed to generalise about its habitat but both the localities where this species is known to occur are on outer reefs bathed in oceanic waters, and due to the local geography, do not receive any major freshwater inputs.

Tridacna squamosa, T. maxima and *T. crocea*

Distribution *Tridacna squamosa, T. maxima* and *T. crocea* are widely distributed and appear in largely the same areas. *Tridacna crocea* is probably the most abundant of the three followed by *T. maxima*.

Habitat These three species have been observed on reef flats, patch reefs, and coral drop-offs, both inside and outside lagoons, although *T. crocea* appears more abundant on shallow reef flats whereas *T. squamosa* has been observed more frequently on shelving fringing reefs.

Hippopus hippopus

Distribution After *T. derasa, H. hippopus* is the least commonly observed species but this may be due to its more cryptic nature. This species has been seen in eastern Guadalcanal, Ysabel, the Marovo Lagoon and Savo, and has been reported from other parts of Western Province, Choiseul, and Sikaiana.

Habitat This species is found mainly on shallow reef or sea grass flats, with slightly muddy or sandy substrates. High densities have been observed in parts of the Marovo Lagoon and Ysabel.

Domestic Utilisation

Tridacnids are a well-known marine resource amongst the inhabitants of coastal communities in Solomon Islands. All of the languages spoken by coastal communities studied so far have different names for most of the tridacnid species that occur locally although *T. gigas* and *T. derasa* sometimes go by the same name as do *T. maxima* and *T. squamosa* (Table 1). Small clams are collected whole whereas generally only the flesh of the larger clams is taken. Women are more frequently seen collecting

TABLE 1. Local names for tridacnid clams in some of the major Solomon Islands coastal languages.

Name of language	Area spoken	*Tridacna gigas*	*Tridacna derasa*	*Tridacna squamosa*	*Tridacna maxima*	*Tridacna crocea*	*Hippopus hippopus*
Ghari	West Guadalcanal	Ghima	—	Inuvitasi	Kapichi	Kapichi	Kwa-kwa
Bughotu	South and central Ysabel	Tungi	—	Fafalehe	Tunuga	Kaspot	Sepila
Marovo	East New Georgia	Ose	—	Veru-veru	Chavi	Ulumu	Hohombulu
'Are'are	South Malaita and East Guadalcanal	Piawa	Sisikeni	Sisimane	Taura	Unupanu	Apuri
Mbilua	Vella Lavella	Siavo	Siavo	Tataikiri	Tataikiri	Tupi-tupi	Moso
Lungga	Ranongga	Iavo	Iavo	Tatakiru	Tatakiru	Gulumu	Moso
Sikaina	Sikaina	Te-tane	Te-tane	Te-kete hatu	Te-veni veni	Te-kunu	Te-pasua
Tavula	West Choiseul	Meka	Meka	Jiku	Qeto	Kasiputu	Mamasivu

TABLE 2. Total exports of non-finfish products from Solomon Islands, 1976–87, excluding crocodile skins (ranked by value).

Products	Rank	Quantity (t)	% of total	Value (SI$)	% of total
Trochus	1	5,120.4	83.2	6,117,634	57.1
Bêche-de-mer	2	522.4	8.5	2,530,737	23.6
Other shell	3	88.1	1.4	729,999	6.8
Black lip	4	204.6	3.3	398,791	3.7
Turtle shell	5	10.9	0.2	370,598	3.5
Green snail	6	126.7	2.1	241,485	2.2
Shark fin	7	6.1	0.1	139,415	1.3
Clam products	**8**	**36.3**	**0.6**	**74,486**	**0.7**
Gold lip	9	16.2	0.3	72,563	0.7
Brown lip	10	19.7	0.3	33,229	0.3
Green lip	11	0.6	0.0	396	0.0

clams from the reef flats and other shallow areas whereas men collect clams while diving or spearfishing.

Consumption

All species of giant clam are widely eaten throughout Solomon Islands and in a number of coastal communities are highly esteemed and form a significant part of the local diet.

Communities which belong predominantly to the Seventh-Day Adventist Church are a notable exception and clams are not supposed to be eaten, for religious reasons, in these areas; mainly Western Province, Rennell, Bellona, and some areas of Malaita.

Coastal villagers have often been observed to collect live specimens of the larger tridacnids from offshore reefs and keep them on nearby reef areas as 'clam gardens.' Usually these clams are kept until required for eating but this is also a common practice even in the areas where clams are not eaten.

Tridacnid clams are sometimes brought, from areas where they are more abundant, into the national capital, Honiara, where their flesh is sold at local markets for about the same price as fish (US$1–2/kg).

Use of Shells

Portions of tridacnid shells are used to some extent for inlays in locally produced carvings, for example in Western Province and eastern Makira. Tridacnid shell is also used in the manufacture of some items of local jewellery such as medallions in Malaita. Large tridacnid shells are sometimes used for ornamental purposes and as pig troughs.

Local Conservation

In the Marovo Lagoon and at the eastern end of Guadalcanal a good local awareness exists of the decline in clam stocks due to overfishing. The establishment of 'clam gardens' by some of the inhabitants of the Marovo area, where clams are not eaten, seems to be for broadly conservationist reasons.

Strong customary rights to marine areas still persist in many parts of Solomon Islands and the holders of these rights may determine the usage of these areas. This customary 'reef-ownership,' coupled with the traditional practice of forming 'clam gardens,' is a cause for optimism regarding future clam conservation attempts and the growing of hatchery-reared clams.

Commercial Harvesting

Available statistics on the export weight and market value of tridacnid clam products are sparse; few local dealers in marine products such as molluscs handle clam shell or meat in Solomon Islands. The export market has been dominated since the 1970s by tuna and tuna products, which have generated exchange earnings of around SI$286 million since 1976. Table 2 indicates the relative importance of the various non-finfish marine exports (excluding crocodile skins), summed for the above period and ranked by value. Between 1976 and 1987 a total of 36 273 kg of clam products (predominantly shell plus some meat) has been exported overseas, with a total value of SI$74 486. Clam products have therefore represented less than 1% of the value of total non-finfish exports for this period.

Exploitation of tridacnid clams is therefore conducted primarily for subsistence consumption or local sale of meat/shells to tourist outlets and restaurants. Only one legal commercial-scale operation to exploit clams and several cases of clam poaching have occurred in the past, and these are detailed below.

Authorised Harvesting

The Taiwanese fishing vessel, Kao Tung #1, received a licence to carry out a trial clam fishing operation in the Marovo Lagoon, in 1983. A total of 1318 clams were harvested in 41 days (Enekevu 1983) most of which were *T. gigas*. This amounted to 1227 kg of adductor muscle. Local reef owners often sold clam meat to the Kao Tung #1. They received US$0.20/kg for mantle meat and US$0.40/kg for adductor muscle. A visit to the same area by CAC staff in 1987 suggested that the clam stocks are still seriously depleted (Govan 1988).

Giant clam shells were harvested in the Marau Sound, at the eastern end of Guadalcanal, about 10–15 years ago. Approximately 25 t of large tridacnid shells were taken locally and reputedly shipped to Japan for the ornamental shell trade. Tridacnids are a highly esteemed food in this area and *T. gigas* is now quite rare.

Poaching

There is evidence to suggest that poaching of the larger species is not uncommon, particularly on the more isolated outlying reefs (e.g. Roncador and Indispensable). The following recent cases have been reported:

In 1982 a Taiwanese clam boat, the Handa Bau, was arrested and convicted for illegal fishing after having already been arrested by Papua New Guinea and being reported in outlying islands for over 3 months (Evans 1983).

In February 1983 another Taiwanese clam boat, the Man Hsiang Huei, was arrested, and subsequently fined, for taking 120 kg of giant clam adductor muscle along the northern coast of Ysabel whilst ostensibly operating under a licence to survey for scallops (Evans 1983).

The Shing Hong #3 from Taiwan was detained in June 1983 near Indispensable Reef and 10 210 kg of 'clam meat' were found on board.

In April 1987 a Taiwanese fishing boat, the Her Cheng Fong #3, was apprehended by the Solomon Islands patrol boat 'Savo' on Roncador Reef. The Taiwanese captain later pleaded guilty to a charge of fishing without a permit. Over 1 t of fresh and frozen clam adductor muscle was found on board the fishing vessel. This was estimated to have come from about 10 000 giant clams of which at least some, and possibly most, were taken in Solomon Islands (G.F. Usher, pers. comm.). The small average size of the adductor muscles seems to indicate that large clams had been removed from the reef at an earlier date. The confiscated muscle was sold to an agent for about US$10 000.

Conclusions

Six species of giant clams occur in Solomon Islands all of which are utilised, although stocks of the larger species are depleted, due in part to local fishing pressure and aggravated by the activities of foreign poachers.

Regulation of the domestic utilisation is very difficult, if not impossible, and it is difficult to adequately police all the areas in Solomon Islands susceptible to poaching due to the distances involved.

Although not to be viewed as a substitute for effective attempts at stock management, the production of farmed clams should ease pressure on wildstocks.

Status of Giant Clams in Tonga

Viliami Langi and Hesitoni 'Aloua*

Abstract

The importance of clams as a local food source for the Tongan people is seen by their daily appearance in the market. There are four species of giant clams in Tonga: *Tridacna maxima, T. squamosa, T. derasa* and *Hippopus hippopus*. No live specimens of *H. hippopus* were found during a 1978–79 survey, although one was reportedly seen in Tongatapu. No *T. derasa* were found in a 1987 survey.

In response to a request by the Government of Tonga, in 1978 Dr John McKoy of the New Zealand Fisheries Research Division conducted a survey of the giant clams (Tridacnidae) in Tonga, funded under the New Zealand bilateral aid program. The survey was conducted in Tongatapu, Ha'apai and Vava'u, the three main centres of the Kingdom.

From December 1978 to March 1979, 72 sites were surveyed, mainly by snorkelling and occasionally using scuba. Clams observed whilst diving were measured in situ, for maximum shell length, to obtain length frequencies, and 125 clams were tagged to assess growth rates. Clams in the local market were also measured. Total meat wet weight was recorded, and gonads were taken for analysis from collected specimens. Relative abundance was estimated by counting the number of clams measured or observed per unit time of searching. Growth was estimated empirically from tagging results.

In considering Tonga's experience of past and present research work, the major practical benefits to the country from surveys conducted, such as the giant clams survey, have been the collection of data enabling management measures to be recommended.

Present Efforts

At present, two government organisations are involved with different aspects of the clam work.

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The Fisheries Division

The Resource Assessment and Development Unit of the Fisheries Division is working on ongoing monitoring and comparative study of the giant clams. The latter study will compare the work done by McKoy in 1978–79 with the present situation. This study started in 1987, and after eight sites were covered the project was postponed to a later date (Table 1). The ongoing monitoring of the clam landings has not started due to the lack of staff.

If one was to draw any conclusions from this small amount of data, it shows that sites that had many clams in 1978–79 have been fished down, and sites with few clams have been more or less left alone. Clams encountered were *T. maxima* and *T. squamosa*; no *T. derasa* were found.

Ministry of Lands, Surveys and Natural Resources

Despite reservations by Fisheries Division, the Ministry of Lands, Survey and Natural Resources, Ecology Division, went ahead with their much-publicised Clam Circle Project. The idea of preserving broodstock of *Tridacna derasa* is to be highly commended. However, it is questionable whether the clams should have been removed from their natural habitat and put into an unsuitable and easily accessible place (in two circles, 66 in outer 33 in inner circle — two circles of clams constitute one colony), inside the harbour lagoon. The assumption was that the clams would survive long enough to reproduce and repopulate the lagoon area.

This project built one clam colony in Nuku'alofa Harbour (placed under security guard since 1986 with replacement of dead clams) and four inside Vava'u Harbour. The circles in Vava'u have at one

TABLE 1. Comparison of giant clam densities at eight sites surveyed in 1987 with same sites surveyed in 1978–79.

Site No.[a]	Locality	Depth (m)	Mean no.[b]/30 min	
			1987	1978–79
19	Malinoa-Fafa	10–14	0	0
18	E. Malinoa Island	0–4	6.5	1.0
17	W. Malinoa Island	0–6	4	0.7
11	NW Fafa Island	0–4	2	4.4
12	SW Fafa Island	0–5	1.5	—
34	NW Makaha'a Island	0–3	3.5	3.3
5	Hakau Mamao	0–6	9.5	19.0
6	Hakau Mamao	0–7	7	22.8

[a] Site numbers from McKoy (1980).
[b] Clams > 100 mm shell length.

time or another been stolen and replaced (Chesher, pers. comm. 1988).

Future Work

The Fisheries Division hopes to continue its comparative study as soon as possible, while getting someone trained (locally or overseas) to do this project alone (Langi 1988).

The latest indications from the Ministry of Lands, Survey and Mineral Resources are they will continue collecting *T. derasa* for their clam circles.

Problems

The management measures (e.g. size regulations) recommended by McKoy (1980) have not yet been acted upon by the government.

When the overseas expert left, aid funds dried up, and coupled with a lack of locally trained staff, monitoring of the resource ceased. When two government organisations work on one resource there will always be differences of opinion on how to go about doing the work.

At present, lack of staff and too many other projects (Langi 1988) involving a limited number of staff prevents the Fisheries Division from keeping up the monitoring effort.

Status of Giant Clams in Vanuatu

Leon P. Zann* and A.M. Ayling**

Abstract

The distribution and abundance of giant clams were investigated at 29 sites on 13 islands of Vanuatu using spot dives, manta tows and belt transects. The following species were recorded: *Tridacna maxima* (common on all islands), *T. squamosa* (uncommon, present at four islands), *T. crocea* (uncommon; present at four islands) and *Hippopus hippopus* (generally uncommon; present on seven islands). Although Vanuatu is usually included in the distribution of *T. derasa* and *T. gigas*, they are either very rare or absent in the group. Stocks of *T. maxima* are secure. *Hippopus hippopus* is overfished on inhabited islands but secure on two remote reefs. The other species are probably naturally patchy in distribution. Protection of *H. hippopus* refuges is recommended, and reintroduction of *T. gigas* should be considered.

THE Republic of Vanuatu (formerly the New Hebrides) is an 800-km long, Y-shaped archipelago of 80 islands lying between 12°S and 21°S and 166°E and 171°E in the Southwestern Pacific. The total land area is about 12 000 km^2, with a Melanesian population of about 112 000. The islands of the south are mainly raised limestone, while those in the north are volcanic. They are tectonically very active; there are several active volcanoes and many islands have been recently uplifted in earthquakes.

There is no continental shelf and all islands fall into very deep water. Most are surrounded by narrow fringing coral reefs, with only occasional development of lagoons. There are only three significant platform reefs in Vanuatu, two of which have cays. Frequent tropical cyclones and coral bleaching (Zann, unpublished data) as well as tectonic uplift (Taylor et al. 1987) are important factors in reef formation.

The coral reefs of Vanuatu have been little studied and little was previously known of giant clam stocks (M. Chambers, pers. comm.). In 1987 the Vanuatu Government approached the Australian International Development Assistance Bureau (AIDAB) and the Australian Institute of Marine Science (AIMS) to conduct an inventory of coral reefs, fish, and selected invertebrates, including the giant clams. This survey was undertaken in March and April 1988. This paper covers the distribution and abundance of the tridacnids in Vanuatu.

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Methods

The survey consisted of a preliminary examination of the archipelago, followed by a detailed survey of one group, Malakula. Twenty-nine sites on 13 islands along the archipelago were examined for geographic trends and to sample a variety of different reef types, habitats and exposures. With the exception of the far northern Torres Group, reefs on all major groups were sampled.

Sites were initially selected from aerial photographs (Royal Australian Survey Corps, 1:30 000) and large scale maps (Institut Geographique Nationale France, 1:50 000 and 1:100 000), and visited by the charter vessel *Coongoola*. About one day was spent at each island during the geographic survey and several days were spent at each site in the Malakula Group. The amount of time at each site determined the survey techniques used, either the rapid, semi-quantitative spot dives and manta board (paravane) tows, or time-consuming quantitative belt transects.

In the rapid surveys the upper reef slopes (< 10 m depths) and lagoon reef patches were examined using 20-min spot dives (snorkelling and scuba) or 2-min manta tows at 2–3 knots behind an outboard skiff. Manta towing allowed a far greater area of

TABLE 1. Distribution and abundance of tridacnids in Vanuatu.

Island, place	Site description and notes	Abundance of tridacnids (no./ha)			
		T.m	T.s	T.c	H.h
Anatom					
Port Anatom	narrow fringing reef (r3; sd; lc 15%)*	16	+	—	—
Inyeug Island	platform reef slope (r3; sd; lc 13%)	50	—	—	+
	lagoon patch reef (r1; sd; lc 30%)	20	—	—	10
Port Patrick	fringing reef, lagoon (r3: sd; lc 14%)	16	—	—	—
Tanna					
Lakariata	fringing reef, slope (r2; sd; lc 25%)	5	—	—	—
Port Resolution	fringing reef (r2; sd; lc 15%)	—	—	—	—
Erramango					
Dillan Bay	fringing reef, slope (r2; sd; lc 40%)	+	—	—	—
Efate					
Lelepa	reef patch, slope (r4; sd; lc 25%)	3	—	—	—
Mallao Bay	fringing reef, crest (r2; sd; lc 38%)	—	—	—	+
Moso Island	fringing reef, slope (r10; mt; lc 20%)	7	—	3	3
*Cook's Reef***	platform reef, lagoon (r7; sd; lc 40%)	10	+	—	25
	platform reef, slope (r10; mt; lc 30%)	5	—	—	1
Pentecost					
(SE reef)	fringing reef, slope (r6; sd; lc 23%)	6	—	—	9
Loltong Bay	lagoon reef patch (r1; sc; lc 16%)	20	—	—	—
Gaua					
Lesalav Bay	fringing reef, lagoon (r7; sd; lc 17%)	9	—	—	1
Ureparapara	fringing reef (r1; sd; lc 25%)	+	—	—	—
*Reef Islands***	platform reef, lagoon (r3; sd/sc; lc 15%)	13	—	—	23
	raised crest. Subfossil *Hippopus* max. 90 cm long	+	—	—	+
Espiritu Santo					
Big Bay	narrow fringing reef, slope (r3; sd; lc 25%)	—	—	—	—
Hog Bay	reef patch in lagoon (r5; sd/sc; lc 30%)	2	—	—	2
Turtle Bay	reef patches in shallow turbid lagoon (r7; sd; lc 27%)	—	—	—	—

T.m: *Tridacna maxima*; T.s: *T. squamosa*; T.c: *T.crocea*; H.h: *Hippopus hippopus*.
* (r: number of replicate samples at site; sd: skindive & sc: scuba dive; lc: live coral cover).
** isolated reefs remote from habitation (>20 km).
+ dead shells only.

reef to be covered, but with an obvious loss of precision. About 150–170 m was covered in each 2-min tow or 20-min swim, and a 5-m wide swathe of reef, depending on topography and visibility, was examined. The total area covered was 750–1000 m^2. Abundances were expressed as numbers per hectare. The identity and number of all clams seen were recorded and the general habitat (depth, aspect, coral cover and diversity) was described. Shorelines, cyclone rubble banks, villages, and raised fossil reefs adjacent to each sampling site were examined where possible.

In the detailed surveys of the Malakula area, clam abundances were estimated using replicate belt transects. At each site, five random 50-m transects were laid down and all clams within 2.5 m of either side were noted, as described by Ayling and Ayling (1986).

Results

Four species of Tridacnidae were recorded in Vanuatu: *Tridacna maxima*, *Tridacna squamosa*, *Tridacna crocea*, and *Hippopus hippopus* (Tables 1 and 2).

Tridacna maxima was recorded from all islands examined and *H. hippopus* was recorded from most islands. *Tridacna crocea* was recorded only at Moso Island off Efate and off Sakau Island near Malakula, and was embedded in *Porites* microatolls. Dead *T. squamosa* shells were recorded at a village at Aneityum and at Cook's Reef, and five clams in the Malakula Group. *Tridacna gigas* and *T. derasa* were not seen in this survey and are probably rare in, or absent from, the archipelago.

The relative abundances of these species throughout the group are summarised in Table 1 and the absolute abundances around Malakula are shown in Table 2.

Discussion

The absence of *T. gigas* and *T. derasa* is anomalous as Rosewater (1965) included the New Hebrides in the distribution of these species. The former is abundant in similar latitudes on the Great Barrier Reef to the west (Braley, This Monograph); was present in Fiji to the east until recently (Lewis et al., This Monograph); and is present in New Caledonia to the south (Munro, in press). Munro (in press) reports *T. gigas* fossils from Efate but considers that it is now locally extinct in the archipelago.

The absence of *T. derasa* may be at least partially attributed to lack of suitable habitats as this species is generally found on oceanic reefs remote from freshwater runoff (Adams et al., This Monograph). While the oceanic reefs of Inyeug Island, Cook's Reef, and the Reef Islands are potentially suitable, their very shallow lagoons and steep reef slopes may not provide significantly large areas of suitable habitat.

The rarity of *T. crocea* is also attributed to a paucity of suitable habitat. The intertidal reef flats where its preferred habitat of *Porites* sp. microatolls exists are limited in extent, possibly because of frequent cyclones and tectonic uplift.

The apparent scarcity of *T. squamosa* may be at least partially an artifact of the sampling methodologies. Because of the speed at which the spot dives and manta towing were undertaken, it was not possible to closely examine each specimen and some *T. squamosa* may have been mistakenly included with *T. maxima*.

TABLE 2. Abundance of tridacnids at selected localities in the Malakula Group (mean of five random 50 × 5 m belt transects, expressed as no./ha).

Island:	Reef Flat				Reef Crest				Reef Slope			
Place/Aspect	T.m.	T.s.	T.c.	H.h	T.m.	T.s.	T.c.	H.h	T.m.	T.s.	T.c.	H.h
Maskelynes												
Matai/SE:exp[a]	—	—	—	—	24	—	—	—	8	8	—	—
Sakau/SE:exp	—	—	—	—	32	—	—	—	16	8	—	—
Sakau/Sm.exp	—	—	—	—	—	—	—	—	8	8	—	—
Sakau/NW:shel	—	—	—	—	—	—	48	—	—	—	—	—
Cook Bay:v.shel	—	—	—	—	—	—	8	—	24	8	—	—
Atcin Island												
SE: exp	—	—	—	—	—	—	—	—	16	—	—	—
Malecula												
Port Sandwitch												
E:exp	—	—	—	—	8	—	—	—	8	—	—	—
E:exp	—	—	—	—	—	—	—	—	—	8	—	—

[a] Compass position of site from centre of island; degree of wave exposure (exp: exposed; m.exp: moderate; shel: sheltered; v.shel: very sheltered).

The significance of humans on giant clam stocks in Vanuatu is unknown but it is well documented that overfishing has led to the local extinction of *T. gigas* and *H. hippopus* in much of the northern and southern Pacific (Munro, in press). They are a popular item in the local diet (the Ni-Vanuatu crew of the charter vessel would collect them at any opportunity) and dead shells were evident around most villages visited. It is probably significant that *H. hippopus* were most abundant on the uninhabited Cook's Reef and Reef Islands, and were not recorded in the detailed surveys in the more heavily populated Malakula Group.

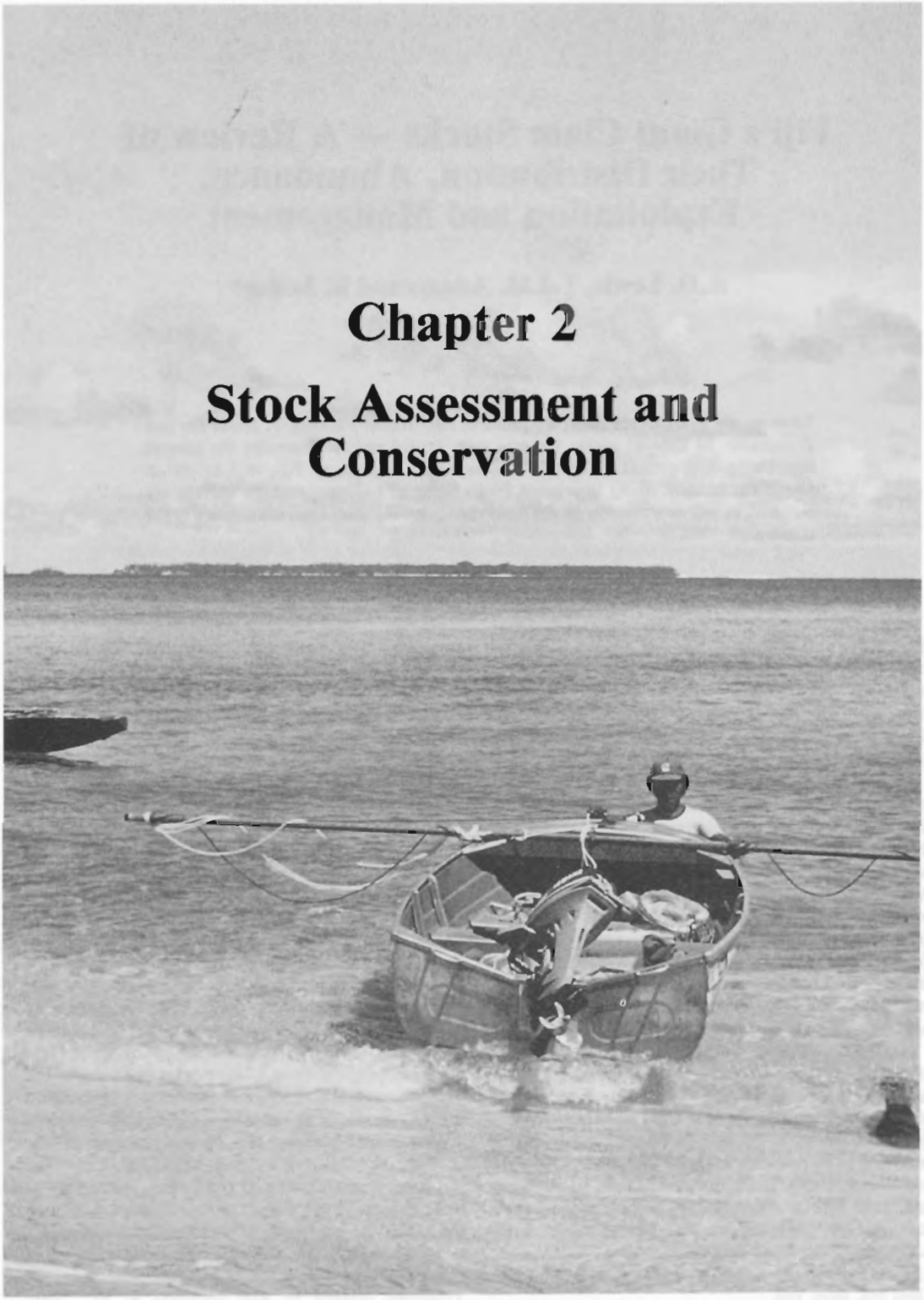
While *H. hippopus* stocks appear to be common on the uninhabited reefs and may act as a breeding pool for the surrounding inhabited islands, the occasional visits by artisanal bêche-de-mer and reef fishermen is a potential problem. It is therefore recommended that the Government of Vanuatu accord these reefs special protection. The reintroduction of *T. gigas* and restocking of *H. hippopus* might also be considered.

Acknowledgments

We wish to thank Dr Marcus Chambers of the Ministry of Lands, Energy and Water Supply of the Republic of Vanuatu who conceived and planned the survey, Dr Terrence Done from AIMS who coordinated the scientific expedition, and the crew of the vessel *Coongoola* who assisted at all times. AIDAB funded this survey, while GBRMPA made available part of the senior author's time.

Chapter 2

Stock Assessment and Conservation



Fiji's Giant Clam Stocks — A Review of Their Distribution, Abundance, Exploitation and Management

A.D. Lewis, T.J.H. Adams and E. Ledua*

Abstract

Three species of tradacnid clams are found in Fiji: *Tridacna derasa, T. squamosa* and *T. maxima*. In 1984–87 major surverys were carried out to determine the general distribution and abundance of giant clams stocks throughout Fiji, and to do an assessment of clam stocks in selected areas. Some of the results of the surveys are included, as well as comments on the future prospects for giant clam mariculture in the country.

Fiji's 300 or so islands of varying sizes are ringed with fringing or barrier reefs, and provide a potentially large area of suitable habitat for giant clams (Tridacnidae: Mollusca). Known locally as vasua, giant clams have traditionally enjoyed high status as a seafood in Fiji (Burrows 1940).

Occurring entirely within areas subject to traditional tenure, they had tended in the past to be reserved as food for special occasions or as a reserve food source in difficult times. The depletion of natural stocks of these desired sessile and highly vulnerable bivalves observed in more densely populated areas of the Indo-Pacific has generally been avoided or at least localised. Until recently, stocks of the second largest species *Tridacna derasa* in Fiji were probably amongst the most abundant outside the Great Barrier Reef of northern Australia.

Increasing commercialisation of the resource, primarily to supply growing local demand from an increasingly urbanised and affluent populace, and growing foreign interest in export possibilities, led to some concern in the late 1970s that the resource may need to be properly assessed and its exploitation monitored. Preliminary Fisheries Division work at that time (Anon 1979, 1980) recommended that commercial exploitation be discouraged and suggested that poaching by foreign vessels may already have been occurring. (This was confirmed by the apprehension of Taiwanese vessels in 1981, 1982 and 1983.)

In the face of growing local commercial production and pressure to allow 'legitimate' foreign exploitation of giant clam stocks, the opportunity to gather information on the distribution, abundance and biological parameters of natural giant clam stocks as a basis for management recommendations was provided in timely fashion by the ACIAR Giant Clam Project which commenced in Fiji in July 1984.

The Fiji Fisheries Division, Ministry of Primary Industries, the nominated cooperating agency, was to place primary emphasis on the survey of natural stocks, in particular those of *Tridacna derasa*, to clarify their biological parameters and utilise these data for the formulation of appropriate management strategies. Unlike other modules of the project, mariculture and reef restocking were initially accorded lower priority in the Fiji project.

This paper reviews the overall results of the project, the history of the exploitation of the resource, current status of the stocks, management strategies and likely future developments. Much of the basic data have been included in the five periodic progress reports to ACIAR. Companion papers examine respectively the population dynamics of *Tridacna derasa* in Fiji (Adams et al., This

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Monograph), attempts to reintroduce *Tridacna gigas* to Fiji (Ledua and Adams, This Monograph), and the discovery of a possible new species of *Tridacna* during the surveys (Lewis and Ledua, This Monograph).

Habitat and Distribution

Of the seven presently recognised species of Tridacnidae (Rosewater 1965, 1982), three occur in Fiji: *Tridacna derasa, T. squamosa,* and *T. maxima. Hippopus hippopus* is now present in subfossil and fossil form in Fiji, with records from the late Pleistocene. The shells are relatively common in coastal middens. There is an apparently contemporary record in the U.S. National Museum, but its origin is unknown (Ladd 1934). *Hippopus hippopus* is also a recent extinction in Tonga (McKoy 1980). An inshore species, it is perhaps the most vulnerable to overexploitation, although underlying causes for its disappearance are not known. *Hippopus porcellanus* is unknown outside the central Indo-Pacific.

The largest tridacnid *Tridacna gigas* appears to have become extinct in Fiji only in the last two decades, the last known live specimen having been collected in the mid 1970s. One uncommon local name, vasua matau, appears to refer to *T. gigas* and large specimens of *T. derasa*. Fiji represents the extreme eastern edge of the species range and it may never have been common. It also approaches the latitudinal limits of the range. On the Barrier Reef, for example, the species is rare south of 19°S (Braley 1988, in press).

Tridacna crocea, the smallest species, has not been observed in Fiji, despite speculation otherwise (Rosewater 1965) and appears not to occur east of Solomon Islands.

Tridacna derasa (Fijian–vasua dina) has a curious NW–SE distribution across the Indo-Malayan region, and is not found east of Tonga or in equatorial areas east of Solomon Islands. In Fiji, the species is generally confined to clear oceanic outer lagoon areas, as noted elsewhere (Braley 1988, in press; Munro and Heslinga 1983), within the protection of well-developed barrier or fringing reefs.

Occurring near the surface down to 25 m, *T. derasa* occurs in greatest density in the windward (eastern) islands of the Fiji group. Very high numbers (hundreds/hectare) are occasionally noted. It is rare or absent from high island fringing reefs and lagoons where salinity and water clarity are reduced by freshwater runoff, and from unprotected areas.

Until a size of typically 30 cm is reached, the species is weakly byssally attached to coral pieces or rubble. The maximum size recorded in Fiji, 62 cm, is well above that recorded by Rosewater (1965 — 51.4 cm) who, however, had access to few specimens. Specimens greater than 50 cm in length are relatively common.

Tridacna squamosa (Fijian — cega) occurs in a variety of habitats, usually weakly attached by a gelatinous byssus to coral pieces and amongst or adjacent to living coral. More tolerant of turbid water than *T. derasa*, it is rarely seen in even moderate density and attains a size of up to 40 cm.

Tridacna maxima (Fijian — katavatu), the smallest of the three species, is invariably partially embedded in coral or substrate with strong byssal attachment. It is relatively common throughout the group, from the intertidal zone down to 10 m or more, in a variety of habitats. It attains high densities in some windward island lagoons where it begins to approach the superabundance observed in eastern Polynesia and has been recorded in Fiji up to 33 cm in length (cf. Rosewater (1965) — 35.3 cm).

A possible fourth species, similar to *T. derasa* in morphology and habitat, has been encountered. Known locally as the tevoro (devil) clam, because of its sharp dorsal valve edges and sinister grey mantle, its status is discussed in a separate paper (Lewis and Ledua, This Monograph).

The habitat and distributional features of these three species within the Fiji group along a generalised east-west cross-section are summarised in Fig. 1.

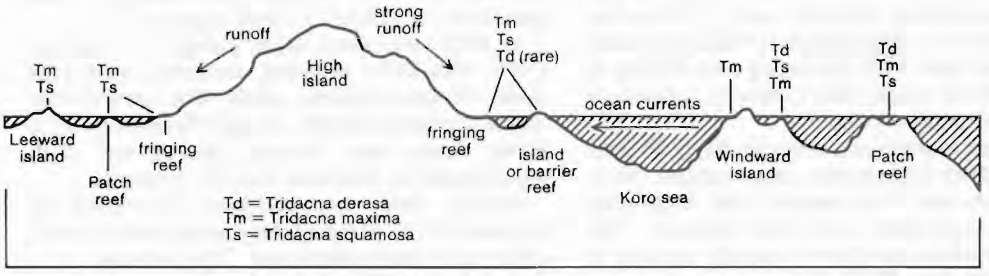

Fig. 1. Habitat and distribution features of giant clams in Fiji, along a generalised cross-section through the group.

Exploitation

Traditional Subsistence Harvest

Giant clam (mantle and adductor muscle) has long been valued by indigenous Fijians, particularly in island communities. After removal from the shell and excision of the kidney (loa), the muscle (uto) and mantle (vasa) is typically cut up and served lightly marinated with lemon juice and coconut milk. It is also occasionally smoked. The shells are put to a variety of decorative or functional uses (e.g. containers, food servers, house mounds, tapa dye mixing) but appear to have been little used for adze blades in Fiji (Moir 1988, in press). The smaller species are generally preferred, the larger *T. derasa* being reckoned tougher and of coarser flavour. Women normally collect *T. maxima* and *T. squamosa* whilst gleaning on the reef flat or in shallow pools. The larger *T. derasa* are collected by diving in deeper water bringing the unattached clam to the surface, a difficult task in depths below 10 m. More recently, dive weights or bêche-de-mer 'bombs' on lines are dropped into the gaping valves of deep specimens, which are hauled to the surface as the valves close tightly. In some areas, clams are kept in 'gardens' near villages as a reserve food supply for periods of reduced food availability, e.g. following cyclones or for important traditional feasts.

As noted earlier, the resource occurs entirely within customary fishing rights areas and its exploitation has been subject to some traditional control. No reliable data on consumption are available. It is clear, however, that even subsistence consumption near populated areas over centuries can severely deplete tridacnid populations.

Small-Scale Commercial Exploitation

Quantities of giant clams, predominantly *T. maxima* and smaller *T. squamosa* and *T. derasa*, are sold in the 11 municipal markets and, more recently, direct to other sales outlets. The clams are usually transported live in the shell and removed for sale at the market.

Market data are imprecise, being a mixture of whole shell and 'meat only' figures, but are a useful indicative guide. Data are available since 1978 and show no consistent upward trend, fluctuating between 4 and 14 t, averaging 10 t. Prices have more than doubled since 1980, averaging over F$2/kg in most markets in recent years (Table 1). Lautoka is the principal market outlet.

Increasing quantities are, however, being directed to other outlets (restaurants, supermarkets, etc.), and supplemented with mantle from large-scale commercial operations (see next section). This source of product has shown a steady increase in sales in recent years (Table 1).

TABLE 1. Production figures for giant clams in Fiji, 1979–87, by outlet type (figures are meat weights in tonnes (mantle and muscle) unless otherwise specified. Subsistence consumption and poaching are not included).

	Outlet type			
Year	Municipal markets[a]	Wholesale and retail outlets[b]	Exports[b]	Yearly total
1979	6.79	—	—	6.79
1980	13.83	0.23	—	14.06
1981	13.41	4.65	—	18.06
1982	11.96	—	—	11.96
1983	12.70	4.62	—	17.32
1984	8.35	33.85	7.3	49.5
1985	7.14	9.46	20.8	37.4
1986	13.74	5.32	11.42	30.48
1987	4.01	17.65	10.69	32.35

[a] Includes some whole shell figures.
[b] More than 95% *T. derasa*.

Commercial Exploitation

Although limited domestic commercial harvest of giant clams had probably occurred prior to 1984, particularly during hurricane relief operations in outlying areas, it was in that year that local operators owning larger vessels geared up to collect clam meat from the outer islands, primarily for the lucrative export market. As this was generally occurring with the full support of local communities, there was no legal restraint to prevent this, and it was seen as a preferred alternative to approved harvest by foreign vessels.

However, a series of exploitation guidelines to provide some safeguards was drawn up by the Fisheries Division and received Cabinet approval in August 1984 (Table 2). Under these guidelines, harvest of the resource was restricted to Fiji nationals, with approval of traditional custodians; export of muscle only was to be prohibited unless evidence was provided of mantle sales, and provision of catch data and export inspection were required.

Total commercial collection of meat (mantle and muscle) for 1984 reached 40 t despite these guidelines, of which 7.3 t were exported.

In 1985 there was a slight reduction in harvest (30 t), with 20.8 t exported, including some 1984 stock. Of these exports, nearly 40% were to New Zealand (mainly mantle), 20 and 9% respectively to Hong Kong and Taiwan direct, and 25% transshipped to Southeast Asia via Australia.

During 1985, one company harvested an estimated 22.9 t of meat from a large mother vessel, using skiffs and hookah gear. This included 15.1 t from a single reef, and 2.9 t from the remote Ceva-

TABLE 2. Guidelines for the exploitation of giant clams (vasua) in Fiji.

The following are suggested for consideration:

i) Harvest and marketing of the resource to be restricted to Fiji nationals.

ii) Harvesting to be carried out at the written invitation of traditional custodians and only on uninhabited islands and reefs in the first instance. Village fishermen to be involved in (commercial) fishing operations to the maximum extent practicable.

iii) Size limits for the three species to be established and strictly observed by harvesters; these size limits would be subsequently incorporated into the Fisheries Regulations.

iv) Provisions to be made for Fisheries Division observers to accompany collecting vessels as deemed necessary.

v) Notice be given in writing by collection vessels of islands/reefs to be visited, together with the written approval of custodians.

vi) Details of catches to be supplied on a per-reef basis or as directed by the Fisheries Division.

vii) Management regimes for particular areas to be determined by consultation between collectors and the Fisheries Division. Possible options include quota (wet weight), selective harvesting (as is done with tree thinning, for example) and reserved sectors where no harvest would be allowed.

viii) All exports to be subject to optional inspection and compulsory licence. A list of approved exporters to be drawn up.

ix) Processing of material prior to export to be strongly encouraged and preference on issue of export licence given to persons processing product.

x) The export of *muscle only* to be discouraged unless markets can be found for the remainder of the edible portion (the adductor muscle may be as little as 10% of the total wet weight).

xi) Consideration be given to the utilisation of the shell itself, which is currently discarded.

xii) Although it remains essentially a matter between collector and resource custodians, the Fisheries Division should do all it can to ensure a fair price be paid and that the harvesting itself is done by them.

These guidelines, to be effective, will require close co-operation between the Division and industry. To date, this has been the case, with industry accepting voluntary restraints on harvesting until policy has been finalised. Maintenance of this spirit of cooperation will be essential to the evolution of a viable long-term fishery.

i-Ra. The vessel was able to operate with impunity essentially because of the support of traditional leaders in the area fished. Because of high overheads associated with the operation of the large vessel the operation was not financially viable, few benefits accrued to the local customary fishing rights owners, and the resource was devastated to no net local benefit.

Partly because of publicity given to the above operation, and partly due to dwindling stocks, commercial operations were scaled down in 1986. Exports dropped to 11.4 t, which included much material carried over from 1985. Just over 3 t were exported during 1986 after March and only 3 kg after June 1986. Commercial activity virtually ceased, and draft legislation to bring the revised guidelines into law had been prepared.

This situation, however, changed again dramatically in 1987, to the detriment of the remaining *T. derasa* stocks. Following the political crisis in Fiji, cash-earning opportunities diminished as the economy contracted, and sedentary exportable reef resources, including bêche-de-mer, mother-of-pearl and vasua, became the focus of interest once again. This was assisted by the formation of an Auxiliary Unit which collected products from outlying islands in a heavily subsidised operation using numerous vessels.

Exports during 1987 rose again to 10.7 t. Much of this was adductor muscle only, with previous requirements for mantle sales now essentially ignored. By early 1988, the Unit had entered into a contract to supply 1 t/month of adductor muscle to a Southeast Asian buyer. It is doubtful whether this can be achieved without dealing remaining *T. derasa* stocks a very severe blow.

Foreign Fishing Activities

With the gradual exclusion of illegal Taiwanese clam fishing vessels from the Great Barrier Reef by the early 1980s (Dawson 1986), these vessels were forced to look elsewhere in the Southwest Pacific for sources of adductor muscle. The outlying areas of Fiji clearly became one such target area, with their still relatively abundant stocks of *T. derasa* in selected localities.

One vessel, the Shin Shing was apprehended in August 1981 on the Great Sea Reef, with fresh clam muscle aboard. In the vessel's deck log was evidence of previous visits by this and other vessels. A second vessel, the Perna Shing was arrested in December 1982, and a third vessel, the Ching Fing, in Kadavu in February 1984.

These vessels represent an unknown fraction of illegal vessel visits to Fiji and their total catch cannot be estimated. Certain villagers on remote outer islands recall regular sightings of vessel lights on remote reefs in the late 1970s and early 1980s.

Another source of illegal clam collection is suspected to be Taiwanese longliners fishing under contract to the local Pacific Fishing Company at Levuka. No data are available on their catches, but it is suspected not to be large by comparison with the distant water vessels operating out of Taiwan.

Surveys of the Resource

Prior to the initiation of the ACIAR project, no information was available on giant clam stocks on a Fiji-wide basis. The foremost objectives of the Fiji module were therefore to investigate: (i) general distribution and abundance of giant clam stocks in Fiji; and (ii) assessment of clam stocks in selected areas. This would include heavily fished areas and areas remote from population centres and would be based on density and size distribution estimates.

Methods Used

As noted by Braley (1988, in press), broad-scale estimates of clam densities are generally lacking although there are numerous estimates in the literature for individual small lagoons and reefs. The area required to be covered during the three years of the project was vast, with 300 plus islands and reefs and an estimated 3000 nautical miles of reef face (Fisheries Division estimate). Because of this, the standard transect approach using weighted lines was rejected as being too time-consuming, and a broad-brush approach involving towing two divers behind a dinghy gradually evolved.

This enables large areas to be covered efficiently, particularly as *T. derasa*, the primary target species, is not especially cryptic and is usually readily seen from the surface. The area covered can be relatively accurately estimated, given a calibrated speed of the vessel and a standard track width. In practice, however, considerable problems remain: (i) with *T. derasa*, the primary target species, occurring in a wide depth range (1–25 m), visibility of the clams and track width both vary widely; and (ii) *T. derasa*-favoured habitat, in particular, is spatially patchy, and confidence limits on any population estimates are inevitably very wide (Munro 1987).

On timed tows, numbers of *T. derasa* and *T. squamosa* were, however, recorded, and a qualitative estimate of relative *T. maxima* abundance made. As a supplementary technique, divers spread out from a given spot for a set time and recorded individual species numbers seen during this time. In this way, an estimate of relative density could be gradually built up for comparative purposes. Numbers of dead (empty) shells were also noted during tows.

Experience rapidly showed that *T. derasa* densities from an overall survey viewpoint were essentially binomial — in simple terms, 'a lot' (up to hundreds/hour) or 'very few' (< 6 individuals/person-hour), and a desirable abundance classification for a broad-brush survey of a patchily distributed species.

Areas were thus rarely surveyed at random. Rather, these were chosen after examination of nautical charts and aerial photographs, the latter proving very useful in identifying the clean sand/coral bommie (massive coral head) back reef habitat favoured by *T. derasa*. Preference was given to uninhabited areas, experience having shown *T. derasa* to be now rare in most areas near habitation.

According to the original project aims, considerable effort was also directed to the collection of representative size structure data of giant clam populations, particularly *T. derasa*, from various areas. Where clam densities were relatively high, samples of 100 clams minimum were measured by free divers. Some 15 *T. derasa* and three *T. maxima* samples, totalling 1765 and 481 individuals respectively, excluding dead shells and tagged individuals, were collected in this way and are analysed elsewhere (Adams et al., This Monograph).

Information was gathered on previous levels of exploitation from the nearest villages wherever possible. In relatively few cases were totally unexploited populations being surveyed. As noted earlier, numbers of dead shells were always recorded, but it was never possible to distinguish in practice between harvest and natural mortality. In any case, it is normal Fijian harvest practice to take away the whole shell, as opposed to the Taiwanese practice of excising the meat in situ with a clam chisel. In the latter regard, numerous areas were encountered where large numbers of shells littered the bottom and density of live *T. derasa* was severely reduced.

Survey Results

A total of 26 survey trips, averaging 7 days each, was made between August 1984 and March 1987. Figure 2 gives an indication of the geographical coverage of those trips.

The survey data as outlined thus provided a picture of current standing stock, rather than natural (unexploited) abundance. Detailed survey data from individual reefs are available in trip reports contained in the various reports to ACIAR, and it is not intended to present them in detail here, for resource security reasons. In some cases, post-survey exploitation has considerably reduced densities as noted earlier.

The following general status report is offered for each species. Species habitat preferences have previously been noted.

Tridacna derasa Widespread throughout the group, but generally rare on the fringing reefs of the main islands where terrestrial influence is strong, and in the leeward islands (Yasawas) where sheltered oceanic lagoons are generally wanting. In 1984–85, there were still abundant populations on various reefs in the windward (Lau, Lomaiviti) islands, but subsequent commercial harvest has considerably

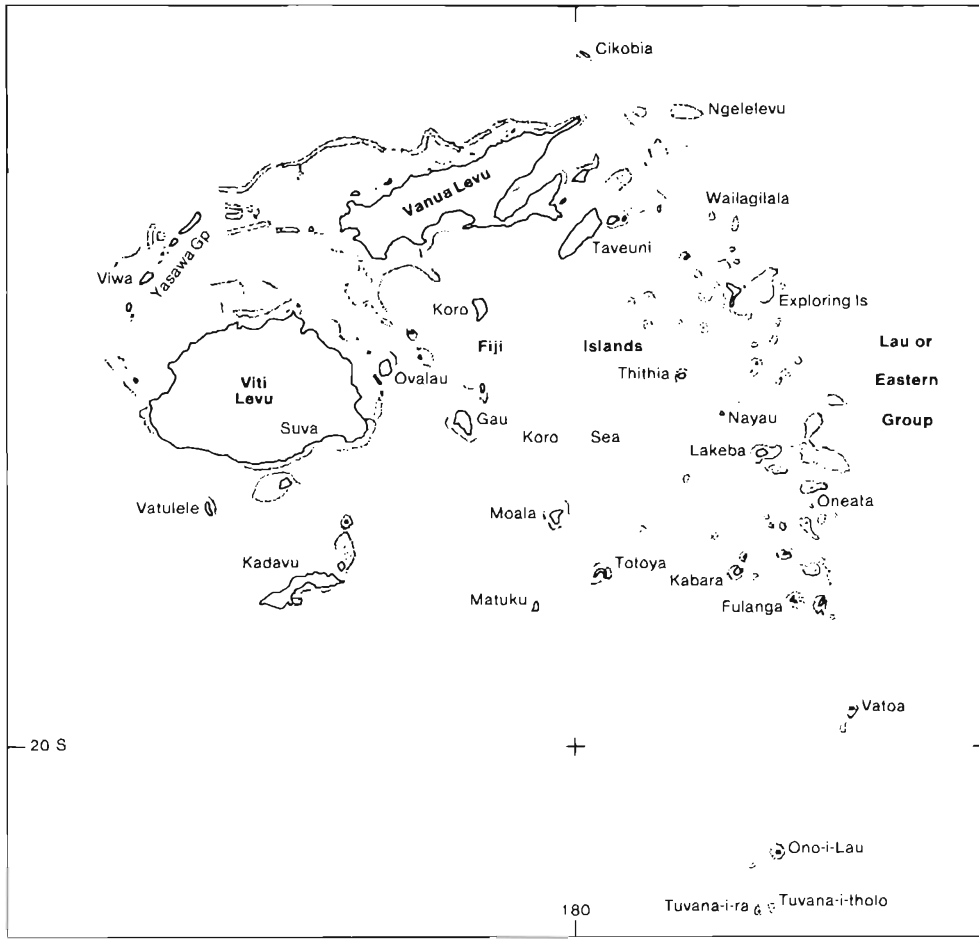

Fig. 2. Reefs surveyed in Fiji waters, 1984–87.

reduced these numbers. Isolated pockets still remain and should be protected. Densities on inhabited windward islands generally low, with remaining individuals in deeper water (10 m plus). Further commercial harvests for export should be prohibited.

Tridacna maxima This is the most abundant species by number and is afforded some protection by virtue of its small size and partial embedment in the coral. It is widespread throughout the group, but densities are now low near major urban centres. Maximum densities are observed in some windward island lagoons, but these are unlikely to support sustained commercial harvest.

Tridacna squamosa Widespread throughout the group, from turbid inshore high island reefs to clear oceanic lagoons. Cryptic and often overlooked in surveys, but never as abundant as *T. derasa* or *T. maxima*. Densities now low near major urban centres.

Conclusions and Future Prospects

Giant clams appear particularly vulnerable to overexploitation, as experience throughout much of their Indo-Pacific range attests. The larger species (*T. derasa* in this case) are very visible, vulnerable and valuable. Growth rates are relatively slow (Adams and Lewis, This Monograph), recruitment appears erratic and limited (Yamaguchi 1977; Braley, This Monograph), and there may be critical density thresholds needed to ensure fertilisation and hence population survival on a local scale.

Commercial harvest targets primarily on old (10 and often 15 years plus) individuals, as smaller

individuals are both rare and considerably less valuable. Any recovery from heavy exploitation in a given area (recruitment overfishing) can be expected to be long-term (15–20 years), provided sufficient broodstock survive to ensure recruitment.

Survey work carried out under the ACIAR project from 1984 to 1986 revealed that, contrary to popular belief, average densities of *T. derasa* in most areas were low, even in highly suitable and extensive habitat. In some cases, this can be attributed to poaching, in others to subsistence collection alone over many generations. High density pockets of *T. derasa* were observed, giving cause for some optimism.

In the last 9 years, however, over 210 t of clam meat, *excluding* subsistence consumption, poaching and unaccounted local sales, has been marketed in Fiji as successively poaching, commercial collection, and subsidised government collection took their toll. Over 120 t of this has been *T. derasa* marketed/exported in the last 4 years, representing more than 120 000 adult clams.

Whilst the guidelines instituted proved useful in stemming this tide, traditional constraints did not, and new political expediencies ultimately saw the guidelines ignored. *Tridacna derasa* has not followed *T. gigas* into extinction and is unlikely to do so, but probably the largest remaining natural stocks outside of Australia have been decimated for limited short-term gain to their traditional custodians.

For *T. derasa* stocks to recover, several options seem desirable. Further commercial exploitation should be halted, exports banned and marine reserves established in suitable areas in consultation with traditional custodians. The government quarantine island and hatchery site at Makogai would be an obvious starting point. Broodstock might be aggregated in severely depleted areas and recovery from exploitation, in areas where pre- and postharvest survey data are available, closely monitored.

The technology is available for the extensive culture of *T. derasa*, if deemed economically feasible, as part of any 'nucleus restocking' program. *Tridacna gigas* has already been reintroduced should broodstock be required for any planned commercial mariculture ventures in the future (Ledua and Adams, This Monograph).

Recruitment of the Giant Clams *Tridacna gigas* and *T. derasa* at Four Sites on the Great Barrier Reef

R.D. Braley*

Abstract

Low levels of recruitment of giant clams, that have been found in other studies, were confirmed again for four study sites on the Great Barrier Reef of Australia from late 1981 to late 1985. However, in early 1987 a major recruitment of *Tridacna gigas* was discovered at Lizard Island. Subsequently, a mapping/tagging survey was carried out. The 127 *T. gigas* recruits found in the 1.2-ha area surveyed were estimated to be 12–18 months old, and is the largest population found to date for this species. This recruitment follows a mass mortality of adult clams, mainly *T. gigas*, at Lizard Island reefs beginning in mid 1985.

NATURAL recruitment of the giant clams *Tridacna gigas* and *T. derasa* is extremely low (Hester and Jones 1974; Yamaguchi 1977; Pearson 1977; Gwyther and Munro 1981; Heslinga et al. 1984; Braley 1984). Yamaguchi (1977) compared this apparent *K*-strategy (Odum 1963) of giant clams to that of whales or forest trees. The high fecundity noted in spontaneous or induced-egg spawnings (Jameson 1976; Beckvar 1981; Gwyther and Munro 1981; and Heslinga et al. 1984) suggests that giant clams should be typical *r*-strategists.

Recruitment surveys were made at four sites with the initial surveys between late 1981 and early 1984. The four sites were Lizard Island (mid-shelf reef), Escape Reef (outer-shelf reef), Michaelmas Cay Reef (mid-shelf reef), and Myrmidon Reef (outer-shelf reef). Surveys were terminated at all sites except Lizard Island by late 1985. A large number of juvenile *T. gigas* were found in January 1987 at Lizard Island and a careful mapping and tagging survey was carried out in April 1987. This paper examines the natural recruitment found at these sites along the north-central Great Barrier Reef.

Methods

Polypropylene lines were laid in parallel 5–10 m apart along the length of each study site. Two or three divers covered the areas between adjacent parallel lines by diving in a zigzag motion over their portion of the area, thoroughly searching the bottom substratum for juvenile clams (less than 30 cm shell length). Either scuba or snorkel was used depending on tides. Diving assistants were shown shells, photographs, or live juvenile *T. gigas* and *T. derasa* to enable recognition in situ. If a juvenile was found it was tagged temporarily with a numbered underwater paper. The juvenile was then measured for shell length with calipers, and in some cases, where feasible, returned to the laboratory overnight for weighing. Estimates of the age of clam juveniles were taken from the growth curves of Beckvar (1981), Munro and Gwyther (1981), Heslinga et al. (1984), and James Cook University (unpublished data).

In the April 1987 Lizard Island survey, prepackaged tagged markers were secured to the reef substratum within 15 cm of the clam juvenile(s). Here, clams were measured in situ to avoid unnatural disturbance. Substratum type(s) immediately surrounding the clam recruits were recorded. The seven substratum types were: (1) soft coral; (2) filamentous algal covered surface; (3) branching *Acropora* sp. coral; (4) coral crevice; (5) other hard coral; (6) coral pavement; and (7) sand/rubble.

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Results

Lizard Island

Watson's Bay (Fig. 1) This site was set up in November and December 1983. A thorough recruitment search was made in December 1985. Three divers covered this approximately 0.55-ha site in 2 days and found only one new *T. derasa*. This clam was 22.1 cm shell length, 1687 g total weight, and estimated to be 3.5 years of age. This recruitment represents 3% of the population of *T. derasa* at Watson's Bay (population level prior to mass mortalities in June and July 1985), and 0% recruitment for *T. gigas* (Table 1).

The April 1987 survey was very different. A size-frequency histogram for 85 *T. gigas* juvenile recruits is shown in Fig. 2. The basically unimodal distribution shows a major recruitment to the reefs by juveniles from the same year-class (see also Table 1). The few juveniles in larger size-classes were probably from a separate, earlier recruitment. The mean size ± SD of juvenile *T. gigas* (≤130 mm) was 105.9 ± 10.3 mm (n = 77).

Palfrey-South Island Channel (Fig. 3) This site was set up in November and December 1983. The first thorough recruitment search was made in November and December 1984, then a second one in December 1985. Three to four divers surveyed this approximately 0.73-ha site in 2 days in 1984

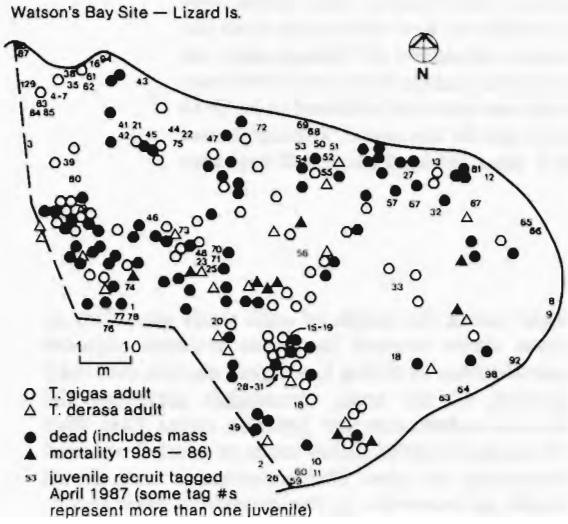

Fig. 1. Tagged adult and juvenile recruited clams at Watson's Bay.

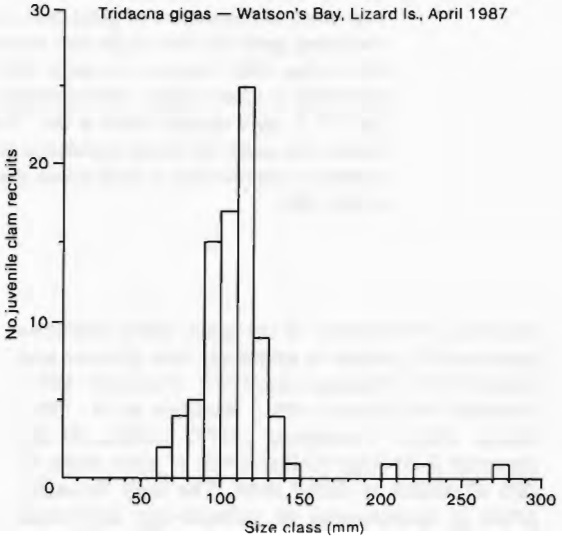

Fig. 2. *Tridacna gigas*, Watson's Bay; size-frequency distribution of natural recruits.

TABLE 1. Recruitment rates of *Tridacna gigas* and *T. derasa* to several reefs between 1982 and 1987.

Site (area)	Date	*T. gigas* recruits % of population/ no. of recruits/ average recruitment (per ha)	*T. derasa* recruits % of population/ no. of recruits/ average recruitment (per ha)
Watson Bay, Lizard Island	12.85	0/0/0	3.3/1/1.8
	1.87	64.4/85/154.5	33.3/8/14.5
Palfrey-South Island, Lizard Island	12.84	2.5/2/2.8	25/6/8.2
	12.85	0/0/1.4 (2 years)	0/0/4.1 (2 years)
	1.87	56.4/44/60.3	18.2/4/5.4
Escape Reef	12.82	1.2/3/2	1.5/3/2
Michaelmas Cay	5.85	0/0/0	10/1/9.2
	5.86	1.2/1/4.6 (2 years)	0/0/4.6 (2 years)
Myrmidon Reef	1.84–10.85	2.5/2/3.4	15.4/4/6.8

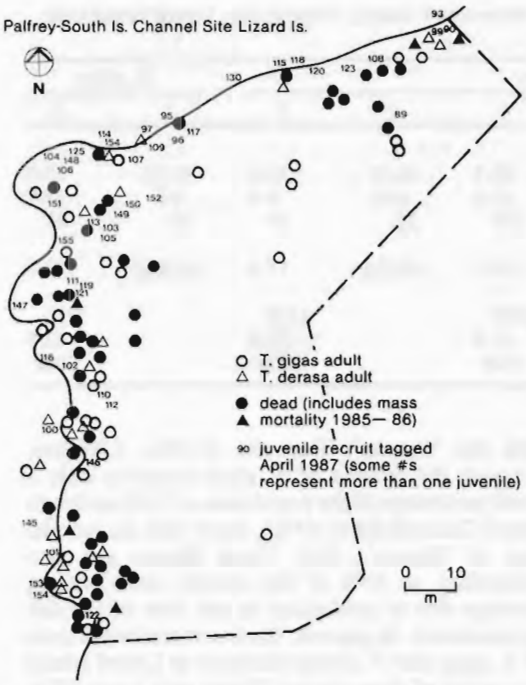

Fig. 3. Tagged adult and juvenile recruited clams at Palfrey-South Island channel.

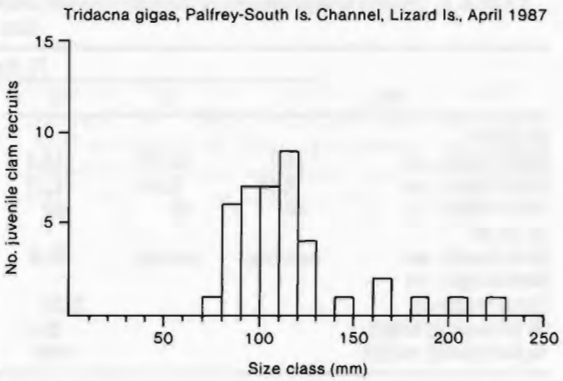

Fig. 4. *Tridacna gigas*, Palfrey-South Island channel; size-frequency distribution of natural recruits.

while two divers surveyed it for 3.5 days in 1985. Six *T. derasa* and two *T. gigas* juveniles were found in 1984. These were tagged, measured and weighed at Lizard Island Research Station (LIRS) (see Table 1) and returned to their original locations. All of these recruits were found near the edge of the channel, generally in branching *Acropora* sp. coral. These recruits represent 25% of the population of *T. derasa* at this site and 2.5% of the *T. gigas* population (both population levels taken prior to the mass mortalities which began in June and July 1985). No new *T. derasa* or *T. gigas* recruits were found in the January 1986 survey. Rather, three of the 1984 *T. derasa* recruits and one of the *T. gigas* recruits were missing within 1 year (Table 1). Broken juvenile *T. derasa* and *T. gigas* shells were seen near one location where live juveniles of these species were located. Tags were not found with the broken shells, however, so predation could not be positively implicated. Growth of these juveniles in 1 year averaged 30.9 ± 12.9% increase in total weight for three *T. derasa*. The single *T. gigas* increased by 53.3% in shell length and 6080% in total weight (Table 1).

Size-frequency histograms are shown for the April 1987 survey for 41 *T. gigas* and 12 *T. derasa* juveniles (four from Palfrey-South site), respectively (Fig. 4). As for the Watson's Bay site, the distribution indicates an important recruitment by juveniles from the same year-class (Table 1).

The mean size ± SD of *T. gigas* was 103.2 ± 14.1 mm (n = 34). The small recruitment of *T. derasa* juveniles here and at Watson's Bay was not sufficient to indicate a model distribution. Table 2 shows the percentage of clams (*T. gigas* and *T. derasa*) associated with a substratum at both Lizard Island sites. Some juveniles were associated with multiple substrata. In such cases each substratum was treated as having that clam's association. Important substrata associated with *T. gigas* juveniles were types 2, 3, and 5. Some clustering of juveniles was evident, but not enough detail on exact position is available to carry out nearest-neighbour analyses.

Escape Reef

This site of approximately 1.5 ha, on three patch reefs, was set up in December 1981 and revisited in December 1982. Few new juveniles were noticed in December 1982. A total of three *T. gigas* and three *T. derasa* less than 14 cm shell length were found. This represents 1.2 and 1.5% of the populations of living *T. gigas* and *T. derasa*, respectively. This size-class (< 14 cm) represents a maximum age of 2.5 years as determined by growth curves for laboratory-reared seed clams of these species, which were subsequently placed on a reef for growth (Heslinga et al. 1984).

Michaelmas Cay

This site of about 0.108 ha was set up in January 1984 and visited at nearly monthly intervals for a 2-year period. The first recruitment survey was done on three trips between 17 March and 11 May 1984. Only one *T. derasa* recruit was found, representing 10% of the *T. derasa* standing stock population. It was 9.5 cm shell length on 11 May 1984, 12.1 cm

TABLE 2. Growth measurements of juvenile recruits from Palfrey-South Island, Channel site, Lizard Island over time.

	T. derasa						*T. gigas*	
No.:	1	2	3	4	5	6	1	2
30.12.84								
Shell length, cm	14.1	13.75	15.1	20.7	12.45	14.0	15.15	15.0
Shell height, cm	8.65	8.85	11.7	12.5	8.45	9.4	9.8	11.7
Total weight, g	40	40	145	170	20	50	50	45
26.12.85								
Shell length, cm	missing	missing	22.0	26.0	missing	17.0	missing	23.0
Shell height, cm			—	—		—		—
Total weight, g			2260	2820		1150		2780
% increase in length			45.7	25.6		21.4		53.5
% increase in weight			1460	1560		2200		6080

on 9 August 1985 (increase of 27.4% in 15 months) and missing by 18 September 1985. No *T. gigas* recruits were found.

A second survey was made on 9 May 1986. Here, only one new *T. gigas* recruit (7.5 cm shell length) was found.

Recruitment surveys made by Queensland Fisheries Service at R.G. Pearson's 2.7-ha clam study site at Michaelmas Cay reef resulted in low recruitment. The total numbers of *T. gigas* and *T. derasa* recruits found among surveys from 1978 to 1985 were 71 and 9, respectively (Munro and Pearson, pers. comm. 1986).

Myrmidon Reef

Two areas of the backreef flat contiguous with the edge of the lagoon comprised this site (approximately 0.39 ha) which was set up initially in January 1984. Recruitment surveys at one or both areas were made in 1984 and 1985, and one on 3 October 1985 with two to three scuba divers (Table 4). Six juveniles were found between the two areas throughout the period of study. Four of these were *T. derasa*, three of which disappeared before the last measurement date. The two *T. gigas* were found at the first survey and remained to the last measurement date. These recruits represent 15% of the *T. derasa* population and 2.5% of the *T. gigas* standing stock population. Percentage increase in shell length is shown for three of the six clams in Table 3. The mean percentage increase of the *T. gigas* individuals in 21 months was 38.6 ± 9.2%. The single *T. derasa* increased in length by 200% in 18 months and 343% in 21 months from 30 January 1984 (Table 3).

Discussion

Lizard Island Sites

Recruitment of *T. derasa* at the Palfrey-South Island Channel site was high (25%) in comparison with the Watson's Bay site (3.3%). Likewise, although the recruits of *T. gigas* comprise only a small percentage of the population at Palfrey-South Island Channel site (2.47%), there were no recruits seen at Watson's Bay. These figures are also misleading, as 50% of the recruits were missing (perhaps due to predation) by the time of the last measurement. In general, the low recruitment rates of *T. gigas* and *T. derasa* observed at Lizard Island are typical of these species (Hester and Jones 1974;

TABLE 3. Substratum type(s) associated with juvenile clam recruits at Watson's Bay (WB) and Palfrey-South Island (P-S) sites. Percent of total clams associated with each substratum is shown; note that when clams are associated with multiple substrata each substratum is treated as having those clam's association.

		Percent of total clams associated with substratum	
Substratum type	Site	*T. gigas*	*T. derasa*
1. soft coral	WB	7.1	12.5
	P-S	2.4	0
2. filamentous algal covered surface	WB	23.5	12.5
	P-S	26.8	0
3. branching *Acropora* sp. coral	WB	35.3	0
	P-S	78.0	75.0
4. coral crevice	WB	14.1	25.0
	P-S	4.8	0
5. other hard coral	WB	40.0	50.0
	P-S	21.9	0
6. coral pavement	WB	15.3	0
	P-S	4.9	0
7. sand/rubble	WB	9.4	12.5
	P-S	14.6	75.0
Total number of clam recruits found:			
	WB	85	8
	P-S	41	4

TABLE 4. Shell length (cm) of juvenile recruits from Myrmidon Reef sites over time. Percentage increase from last measurement shown in parentheses.

	T. derasa				*T. gigas*	
No.:	1	2	3	4	1	2
30.1.84	7.0	11.5	—	—	28.0	25.5
14.4.84	—	—	19.0	—	—	—
12.6.85	20.0 (200%)	missing	—	15.5	—	—
3.10.85	31.0 (55%)		missing	missing	37.0 (32%)	37.0 (45%)

Yamaguchi 1977; Pearson, pers. comm. 1983) but disturbing in light of the mass mortalities of adult clam populations in mid 1985 and continuing in 1986 around Lizard Island (Alder and Braley, This Monograph). Here, 25% of the adult populations of *T. gigas* and *T. derasa* died in June and July 1985, 33% by December 1985, and 57% by January 1987. These mortalities were not restricted to any size-class. There were greater numbers of *T. gigas* than *T. derasa* affected by the mortalities. An unknown ciliated protozoan was suspected from histological preparations. Mass mortalities such as this could decimate dense populations and potentially affect reproductive success.

The April 1987 recruitment survey was successful in that it provided a data base for a significant recruitment of *T. gigas*. These data will be of considerable importance to the management of *T. gigas* populations in the Great Barrier Reef region, by producing unique data on growth and survival of natural recruits. Selective survival due to substratum type may be verified with resurveys and it is possible to compare growth and time to maturity of these naturally recruited juveniles to hatchery-reared clams. The tagged juveniles are being monitored by the Queensland National Parks and Wildlife Service — Marine Parks, Cairns.

Escape Reef

Very low levels of recruitment for *T. derasa* (1.5%) and *T. gigas* (1.2%) were found here. Though recruitment rates were low at a high-density population site such as Escape Reef, it is reasonable to suggest that the few reefs with high-density populations of clams may dominate recruit production for extensive areas of the Great Barrier Reef (Braley, in press). The larval settlement and subsequent recruitment from successful mass spawnings may occur on the parent reef or elsewhere, depending upon currents, gyres or other factors.

Michaelmas Cay

The small size of the study area (0.108 ha) here may account for the single *T. derasa* and lack of *T. gigas* recruits encountered in such a high-density area of giant clams. The Queensland Fisheries Service giant clam site set up by R.G. Pearson in the mid 1970s was located about 1000 m from our study site. Low recruitment was found after intensive searches by scuba divers in 1978, 1979, 1980, 1981 and again in 1985 (Pearson and Munro, pers. comm. 1986).

Within our study site at Michaelmas, the front edge of the mapped area is bordered by sand from the cay and associated sand spit. The instability of this front zone where coral meets sand was seen during February through August 1985 when wind and wave action shifted the sand spit so that adult *T. gigas*, soft corals, and hard corals were killed by being buried in sand. This dynamic zone would obliterate small recruits, but beyond the edge of the sand and coral boundary the effect would be far less damaging.

Myrmidon Reef

The recruitment rate of *T. derasa* was moderately high (15.4%) compared with *T. gigas* (2.5%). However, the population at all study sites is relatively low for *T. derasa* when compared with *T. gigas*. If the life expectancy of *T. derasa* were shorter than *T. gigas* (no conclusive evidence of this from any studies at present), then the higher recruitment rate of *T. derasa* might be expected.

General

Annual natural mortalities of *T. gigas* at Myrmidon Reef (1.5%), Escape Reef (2.0%), Michaelmas Cay (2.25%), and Lizard Island (Watson's 0.84%; Palfrey-South 1.44%), prior to the unusual mass mortalities of 1985–86, would indicate that there is close to a break-even point of recruitment vs mortality. Annual natural mortalities of *T. derasa* at these sites were: Myrmidon Reef (0%), Escape Reef (1.4%), Michaelmas Cay (6.25%), and Lizard Island (Watson's 0%; Palfrey-South 2.72%), prior to the 1985–86 mass mortalities. The major recruitment noted from the April 1987 survey at Lizard Island may compensate for the mass mortalities at that location.

Natural Population Dynamics of *Tridacna derasa* in Relation to Reef Reseeding and Mariculture

T.J.H. Adams, A.D. Lewis and E. Ledua*

Abstract

Tridacna derasa has a patchy distribution, and is not found in great numbers in Fiji. It is the second largest species of Tridacnidae and has considerable mariculture potential. A better understanding of the biology and life cycle of *T. derasa* will enhance efforts to culture the species to restore depleted stocks.

TRIDACNA DERASA is the second largest species in the giant clam family. It has great maricultural potential but, compared with the other species of Tridacnidae, comparatively little is known about natural populations. Field research has concentrated on *T. gigas* (the largest and fastest-growing species) and *T. maxima* (the most widespread species). A better understanding of the biology and 'behaviour' of *T. derasa* is needed to complement efforts in mariculture aimed at enhancing the natural stocks of depleted areas.

There has been some debate in the past about the relative merits of *T. derasa* and *T. gigas* for clam-farming. But do the two species have different ecological requirements? It is likely that they will suit different environments and socioeconomic strategies, and it is hoped that comparative data will soon become available to address this question.

Tridacna derasa has a peculiarly patchy geographical distribution. Although its nominal range extends from the Cocos Islands in the west to Tonga in the east, it is by no means common in many areas within its range. In 1984, at the inception of the International Giant Clam Project, Fiji probably had the largest stocks of *T. derasa* outside the Great Barrier Reef, and was considered extremely suitable for a study of natural populations.

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Habitat

A preliminary indication of habitat preference in any commercially important organism can always be obtained from fishermen. In Fiji, harvesting has concentrated on the windward Lau group of islands. Indeed, commercial records strongly suggest a decline in abundance from east to west over the Fiji group.

This distribution can be largely explained by two major factors: (1) the presence or absence of enclosing barrier reefs, and (2) the size of the island.

There are six major island groups in Fiji. Over 75 individual reefs have been surveyed during the 3-year International Giant Clam Project in Fiji, but a summary only will be presented here.

1. The **Yasawa/Mamanuca** group to the extreme west. The Yasawas almost completely lack enclosing barrier reefs and *T. derasa* is rare. The Mamanucas begin to acquire enclosing reefs to the south, but are close to the main island of Viti Levu, and only isolated low-density pockets of *T. derasa* are found.
2. The **Kadavu** group in the south. Kadavu is a large, high island and *T. derasa* is generally rare. To the north is the large lagoon enclosed by the Great Astrolabe barrier reef, but *T. derasa* does not appear until the extreme north. Along the south of Kadavu the pattern is repeated and *T. derasa* is only found where the barrier reef forms pockets well away from land.
3. **Viti Levu** and associated islands. The largest island in Fiji. *Tridacna derasa* is rare around the coast and at low density near offshore islands.

4. **Vanua Levu** and associated islands. The same situation obtains. *Tridacna derasa* is only found where the barrier reef moves well offshore.
5. The **Lomaiviti** group. These islands are somewhat intermediate, being of moderate size, but usually surrounded by a barrier reef. *Tridacna derasa* is, or was, present in moderate densities.
6. The **Lau** group. This chain stretches 400 km down the extreme eastern edge of Fiji. In general, the islands are characterised by small size and the presence of enclosing barrier reefs, with many submerged atolls. *Tridacna derasa* was formerly found at high densities on many of these reefs.

In general, it can be said that *T. derasa* in Fiji is associated with small islands (probably due to factors of freshwater runoff and water turbidity) which have enclosing barrier reefs (either due to protection from wave action, or a concentration effect on pelagic larvae).

One further factor that complicates the equation is the size of the barrier reef. Fewer *T. derasa* are found in large lagoons. One extreme example comes from the Great Sea Reef, which stretches 240 km along the northern edge of the Fiji archipelago. It is noticeable that *T. derasa* is only common in pockets where the reef splits to enclose small lagoons.

The very highest densities of *T. derasa* are found in the lagoons of small submerged atolls, or in the convolutions of larger reefs well away from high islands.

With regard to microdistribution, *T. derasa* is generally associated with live, hard coral and is typically found clumped on the sand or rubble around coral outcrops. Large *Porites* domes are rarely colonised, but *Acropora* thickets appear to be particularly suitable. Many of the large, dense populations that we have taken length-frequency samples from have been associated with high, vertical coral walls. These may contain up to 100 individuals/ha over small areas.

This, then, broadly defines the habitat preferences of natural populations of *T. derasa*. However, at present, we have no way of knowing whether or not these constraints are effective only on the larval or juvenile stages of the life cycle, or act throughout the adult stages also. For the purpose of enhancement or reintroduction of natural stocks this is irrelevant: such stocks will have to be left to themselves eventually, and chosen sites should approximate optimal natural conditions as closely as possible. But for the purposes of clam farming, where the population is continually replaced by hatchery-grown spat, it may well be that adults or subadults can grow in sites which would not otherwise support recruitment of natural populations.

It is likely that full oceanic salinity and low turbidity remain a critical factor throughout the whole life cycle. The gill morphology of *T. derasa* suggests that it is much more likely that the gills will become clogged with silt than *T. gigas* (R. Braley, pers. comm.). However, the requirement for 'shelter' in the form of small, enclosed barrier reefs or high coral walls, may be factors only infuencing larval concentration or juvenile settlement.

Juveniles of *T. derasa* are usually found in shallow water, byssally attached to coral rubble on the top and sides of coral outcrops. The byssal attachment has been known to persist until the clam is 31 cm in size and sexually mature. When the byssus is detached, the clam falls into deeper water and adults are usually found lying on the sand around coral outcrops, or in hollows and ledges on the outcrop itself.

There is no correlation between size and depth for free-living (non byssally-attached) *T. derasa,* whereas some size stratification might be expected if adults were adversely affected by wave-induced turbulence. At least, this is the case for untouched populations. In areas with a long harvesting history there is marked stratification. Since artisanal harvesting is generally confined to waters less than 5 m deep, the average length of clams in shallow water is much reduced due to the regular removal of older individuals.

Population Structure

During the course of abundance surveys, observations were made on several dense, largely unharvested populations of *T. derasa*. When length-frequency measurements were made, a typical distribution was found (Fig. 1), suggesting low, erratic recruitment, slow adult growth, and low natural mortality.

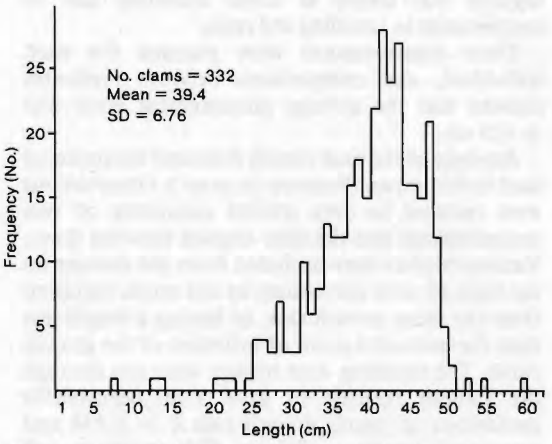

Fig. 1. A typical length-frequency distribution for *T. derasa* in Fiji.

Growth

There has been little information available on the growth of adult *T. derasa* until recently. Information from the Great Barrier Reef (Munro and Pearson, in prep.) and the Fiji study can now be added to the substantial body of data on the growth of juveniles obtained from maricultural work in Palau and elsewhere.

Consideration of Fig. 1 should indicate that methods of estimating growth using modal progression techniques, such as ELEFAN, will be of little use. Such methods require that animals have a definite, restricted spawning season (not true of *T. derasa*, particularly near the equator — G. Heslinga, pers. comm.) and that intra-year-class variation is minimal compared to yearly growth increments, so that modes can be separated (not true in giant clams where, even in maricultured juveniles, the range of size in a single cohort can be twice the yearly growth).

The most reliable method of estimating growth is by remeasuring tagged individuals and for such sedentary animals, with no 'recapture' problems, this method is very easy to apply. An alternative to tagging, when identifying individuals for remeasurement, is to arrange the clams in lines or circles. This has the advantage in that there are no tags to lose, and it is also very easy to see when clams go missing. On the other hand, unless they are nearby, there is the danger of taking the specimens out of their optimal habitat or in damaging them during relocation.

In Fiji, over 200 individuals of *T. derasa* were tagged at one particularly densely populated site, and remeasured at yearly intervals. The tags used were 2-cm diameter red plastic discs, laminated with a number, and were attached in situ using underwater-setting epoxy mortar after the shells had been given a vigorous wire-brushing. Substantial tag-loss was found at some locations due to inexperience in handling the resin.

Three measurements were planned for each individual, and comparisons between replicates showed that the average measurement error was ± 0.5 cm.

Analysis of the data closely followed the protocol used by Munro and Pearson (in prep.). Observations were reduced to data triplets consisting of two measurements and the time elapsed between them. Various triplets were excluded from the dataset on the basis of such constraints as too much variation from the mean growth rate, or having a length less than the estimated point of inflexion of the growth curve. The resulting data triplets were run through the Fabens routine to give Von Bertalanffy parameters of yearly growth rate $k = 0.134$ and asymptotic length = 47.3 cm. This compares well with results described by Munro (This Monograph) for a population of *T. derasa* at a similar latitude on the Great Barrier Reef.

It also compares well with the rule-of-thumb used at MMDC in Palau for the juvenile stages of maricultured *T. derasa* (G. Heslinga, pers. comm.) where growth is essentially linear for the first five years, up to 25 cm in length.

In Yap (C. Price, pers. comm.), juvenile *T. derasa* obtained from Palau have been outplanted and observed for several years. The growth here, too, was essentially linear and averaged 5 cm/year up to 25 cm, after which an abrupt lowering of the growth rate was observed. Twenty-five centimetres approximates the length at female-phase sexual maturity in Palau, and in Fiji it is noticeable that individuals of *T. derasa* over 25–30 cm appear to put more effort into shell thickening than extension growth.

Giant clams appear to have a definite biphasic growth curve, and this 25–30-cm size range after approximately 5 years growth may be the optimal harvesting time for commercial clam farms.

Recruitment

The number of juveniles found in our surveys has been low — either recruitment is erratic and certain age-classes are missing from the surveyed populations or else we are not picking up existing individuals by our survey method.

To rule out the latter, we have made several intensive searches of small areas where high densities of adults are present. Although juvenile *T. derasa* are harder to see than adults, since the visual background is usually coral, they are definitely findable when present. Usually, three or four are found close together, and enough have been found attached to the inner surface of dead adult shells to suggest that available free habitat is a constraint upon settlement. Indeed, dead shells may make suitable artificial spat collectors. However, even intensive searches do not turn up missing age-classes and it is assumed that recruitment is erratic (supported by observations on Great Barrier Reef populations; R. Braley, This Monograph) and lately, at least, sparse.

Since giant clams are sedentary and rely on the release of eggs and sperm to effect fetilisation, reproduction is probably strongly dependent on the density of the local population. The comparatively slow growth and low recruitment suggest that sustainable harvesting levels are low; certainly less than the average 70% of standing stock (on a reef-by-reef basis) than has been the case in Fiji over the past few years. It is strongly recommended that Indo-Pacific countries take measures to set up reserves, or protected areas, for the purpose of aggregating broodstock as a cost-effective way of enhancing recruitment.

Observations on a formerly densely populated site, where about 50% of the standing stock was taken by Taiwanese poachers about 10 years ago, suggests that regeneration does occur, but it is clear that at least another 5–10 years without harvesting will be necessary before the population approximates the natural state. However, at this site, there was also a large untouched stock in deeper water nearby. Observations on more heavily fished areas are inconclusive, but we will be monitoring several sites over the next few years where the history of harvesting is well-known. At one small ring-reef, a recent harvesting operation reduced the population to less than 1% of its formerly dense level.

Mortality

Little can be said about mortality rates at present, save that natural mortality appears to be low compared to that of most other marine organisms, and that fishing mortality is often extremely high.

The use of catch curves to estimate mortality is fraught with problems when growth is slow and recruitment erratic. However, for sedentary organisms, estimation of mortality is easily (though lengthily) accomplished by direct observation, and Munro (This Monograph) presents data on mortality rates in tagged populations on the Great Barrier Reef.

After sexual maturity, predators appear to be scarce. We have had reports of turtles eating adult giant clams which have been weakened by relocation, but in general the main predator is people. Before maturity, pyramidellids, cymatids and fish all take their toll. It has been suggested that *T. derasa* is more resistant to predation in the juvenile stages than *T. gigas* since shell-thickening occurs earlier and shells close more tightly.

Conclusion

Giant clams in general are slow-growing, long-living organisms with erratic recruitment, and *T. derasa* is no exception. This species is adapted to clear-water, barrier-protected lagoon environments and appears to be particularly suited to small islands and atolls, whereas *T. gigas* is adapted to more turbid waters near larger islands and landmasses.

It may be true that *T. derasa* is more resistant to predation and translocation than *T. gigas* and we hope to carry out comparative tests in the future. On the other hand, growth rates of *T. derasa* in ocean-nursery environments are slower. Monthly growth rates for *T. derasa* juveniles are around 4–5 mm/month (Philippines, Palau, Yap) whereas *T. gigas* grows at 6–8 mm/month (Philippines, Australia) for the first 4–5 years. Results from tagged natural populations of both species, in (presumably) optimal environments suggest that a similar differential extends into later stages of the life-cycle.

Each country will have to consider the trade-off in the light of its own circumstances. At this preliminary stage, Fiji is considering *T. derasa* for village-level extension work on smaller islands, and possibly *T. gigas* at a later stage for large-island coastal commercial farms, once the reintroduced broodstock are mature.

However, because it has a different geographic range from *T. gigas*, *T. derasa* may be the only realistic option that many countries have for farming or restocking giant clams, when restrictions on introducing species outside their natural ranges are taken into account.

A Possible New Species of *Tridacna* (Tridacnidae: Mollusca) from Fiji

A.D. Lewis and E. Ledua*

Abstract

During surveys of giant clam stocks in Fiji in 1985, several specimens of clams with a sharp-edged shell and warty grey mantle were found. Although closely related to *Tridacna derasa*, it is readily distinguished from it and may represent a new species of *Tridacna*. A detailed description is given.

GIANT CLAMS are conspicuous and relatively well studied components of the Indo-Pacific coral reef-associated fauna, largely because of the interest their size and unique trophic adaptations generate. Despite this, a new species of giant clam, *Hippopus porcellanus*, was described earlier this decade (Rosewater 1982). This brought to seven the known extant species of Tridacnidae, which are restricted to the tropical Indo-Pacific.

During a 3-year survey of giant clam stocks in Fiji conducted as part of the ACIAR Giant Clam Project, a distinctive giant clam morph, closely related to *Tridacna derasa* but readily distinguished from it, was encounted in small numbers in the windward (eastern) islands of the Fiji group.

This paper provides details of this possible new species, attempts to establish its status, and outlines plans to secure its continued survival.

History

During commercial collection of giant clams in the eastern (Lau) islands during August 1985 for the processing and export of their meat (Lewis et al. This Monograph), collectors noticed amongst the *T. derasa*, which comprised over 95% of the harvest, several specimens with a sharp-edged shell and warty grey mantle. Local villagers at this island (Vatoa) claimed familiarity with the clam morph, which they knew as the tevoro or devil clam. Several photographs were taken of the mantle, and two pairs of intact shells returned to Suva for Fisheries Division examination.

Our intitial reaction was to place the morph at one end of a continuum of *derasa* intraspecific variation in shell shape and mantle colour. *Tridacna derasa* on subsequent ongoing surveys were, however, subject to much closer scrutiny and in January 1986 a similar individual (amongst the many hundreds of *T. derasa* observed) was discovered at Cakau Tabu, a reef complex 130 nautical miles to the north of Vatoa. As no suitable equipment was available on board to transport this unexpected find, the animal was killed and frozen, and the shells retained. (This specimen was later lost during floods which devastated the Fisheries Division at Lami in March 1986.)

Another visit to Vatoa in June 1986 by the project staff produced no further specimens, so a reward of F$50 for live specimens was posted. Of a total of 300 + clams harvested around Vatoa Island in October 1986, six were reportedly tevoro clams. Three were saved, and a trip made to retrieve them in mid November 1986. Two had not survived, and the other was in poor condition in the holding area (2 m of water, in front of the village). It was nevertheless transported to the quarantine facility at Makogai but did not survive. The flesh was preserved in formalin.

A third visit was made to Vatoa in January 1988, after notification that four more tevoro clams had been collected. Careful searching whilst at the island produced another specimen, in 20 m of water. This showed great sensitivity to sunlight when brought to the surface. Four clams (one died in the holding

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TABLE 1. Collection details of tevoro clams.

Date	Area	Collector	No.	Notes
August 1985	Vuata Vatoa (19°56'S, 178°17'W)	A. Robinson	2	Shells only; photographs of animal.
January 1986	Cakau Tabu (17°40'S, 178°32'W)	Fisheries Division	1	Collected at 14 m depth. Viscera frozen, later lost in flood.
October 1986	Vatoa Island (19°49'S, 178°13'W)	Villagers	3	Others collected but not kept; two died before collection, one at Makogai (viscera sent to Australia Museum).
January 1988	Vatoa Island (19°49'S, 178°13'W)	Villagers	2	Three transported to
	Vuata Vatoa (19°56'S, 178°17'W)		2	Makogai but later died
January 1988	Vatoa Island (19°49'S, 178°13'W)	Fisheries Division	1	Transported to Makogai but later died.
April 1988	Vatoa Island (19°49'S, 178°13'W)	Villagers	10	Awaiting collection.
	Komo Island	Villagers	5	Awaiting collection
	Namuka Island	Villagers	4	Awaiting collection.

area) were transported the 220 nautical miles to Makogai (24 hours steaming) in a 500-l tank. All subsequently died in the holding area over a period of 2 weeks, after appearing quite healthy at the end of the first week.

Reasons for this mortality are not clear. The specimens were stressed and gaping on arrival after the long sea trip, leaving them vulnerable to predation, but appeared to recover. Their natural habitat, however, appears to be deeper water (15–20 m) and, given their sensitivity to sunlight, they were possibly unsuited to the holding area (3 m depth).

Following more widespread publicity, tevoro clams were reported by villagers from Komo (5) and Namuka (4) islands, 60 nautical miles to the north. Another 10 clams are currently held at Vatoa (early 1988). A decision on the future of these 10 individuals is pending but it is likely at least half of them will be carefully transported to Makogai and initially kept in protective cages at suitable depths. Provided good survival is achieved, attempts will be made in the long term to induce spawning in shaded conditions.

Collection details of all tevoro clams taken to date are summarised in Table 1. The following details follow Rosewater (1965).

Details

Habitat Recorded only from the eastern (Lau) islands of Fiji, in moderately deep (14–20 m) in clear oceanic water, typically on the outside slope of leeward reefs.

Shell Morphology Shells large, reaching 53 cm length; semicircular in outline, angle formed at umbo exceeding 150°; weak byssal orifice; valves relatively light, with limited thickening at umbo; radial sculpture consisting of six or more folds which are characteristically marked by undulate dark red bands near the umbo; concentric sculpture not strongly expressed, with closely spaced fine lines of growth; dorsal valve margins only slightly undulate, and with very shallow interdigitation; dorsal edge very sharp and thin; hingeline about equal to half shell length; umbo located posterior of centre; a shallow groove running anteriorly from the umbo (cf. *derasa*); valves only slightly concave, enclosing a relatively small internal volume; area enclosed by pallial line modest in size.

The Animal Mantle rugose, with numerous warty protuberances and brownish-grey in colour, without striations; incurrent siphon tentacles longer and larger than *derasa*.

Morphological and other differences between *derasa* and the tevoro clam were noted. A size range of tevoro clams of 26–53 cm is represented. In the Vatoa area, overall relative abundance of the two morphs (*derasa*/tevoro) may be of the order of 50:1 or more.

Taxonomic Status

On the basis of the single preserved specimen of tevoro clam examined by him and two *T. derasa* consigned at the same time, Dr W.F. Ponder (Division of Invertebrate Zoology, Australian Museum) concluded that it was probably an unnamed taxon, although more material (including juveniles) would be needed to confirm this.

Assuming this is so, the tevoro clam is sufficiently

rare to make it unlikely that a full size range of individuals will ever be collected. The relative rarity of *T. derasa* juveniles, believed to be the result of limited, erratic recruitment and low juvenile survival (Adams et al., This Monograph) suggest that tevoro juveniles will probably be encountered very rarely indeed, assuming similarity in population structure to other large tridacnids.

This then casts some doubt on the long-term survival of the taxon. Recent commercial exploitation in the restricted area from where it has been recorded has already severely depleted *T. derasa* stocks and, one assumes, tevoro numbers at the same time. Its apparent preference for deeper water habitat outside the reef may, however, offer some measure of protection.

Assuming the species does not occur elsewhere (this cannot be completely discounted because of the close similarity to *T. derasa*), it is interesting to speculate why it has survived in Fiji.

Fiji occupies an interesting zoogeographic location with respect to the distribution of extant giant clam species. Of the seven known species of Tridacnidae (Rosewater 1965, 1982), the largest, *Tridacna gigas*, appears to have occurred no further east than Fiji, where it is now extinct (Lewis et al., This Monograph). Two other species, *Hippopus hippopus* and *Tridacna derasa*, find the eastern limit of their distribution in Tonga, only 200 nautical miles to the east of Fiji. (The former species is now extinct in both countries.) The distribution of these species may be implicated with the tectonic history of the region, the Pacific Plate boundary lying just to the east of Tonga. However, two other tridacnids, *T. maxima* and *T. squamosa*, are widely distributed from East Africa to Polynesia.

It could be hypothesised that the tevoro clam is a relict population on the eastern edge of both its own former range and that of the apparently more abundant and successful *T. derasa*. It still remains entirely possible, however, that due to its deep-water habitat and close superficial similiarity to *T. derasa*, other populations may be located within the curiously patchy distribution of that species.

Future Plans

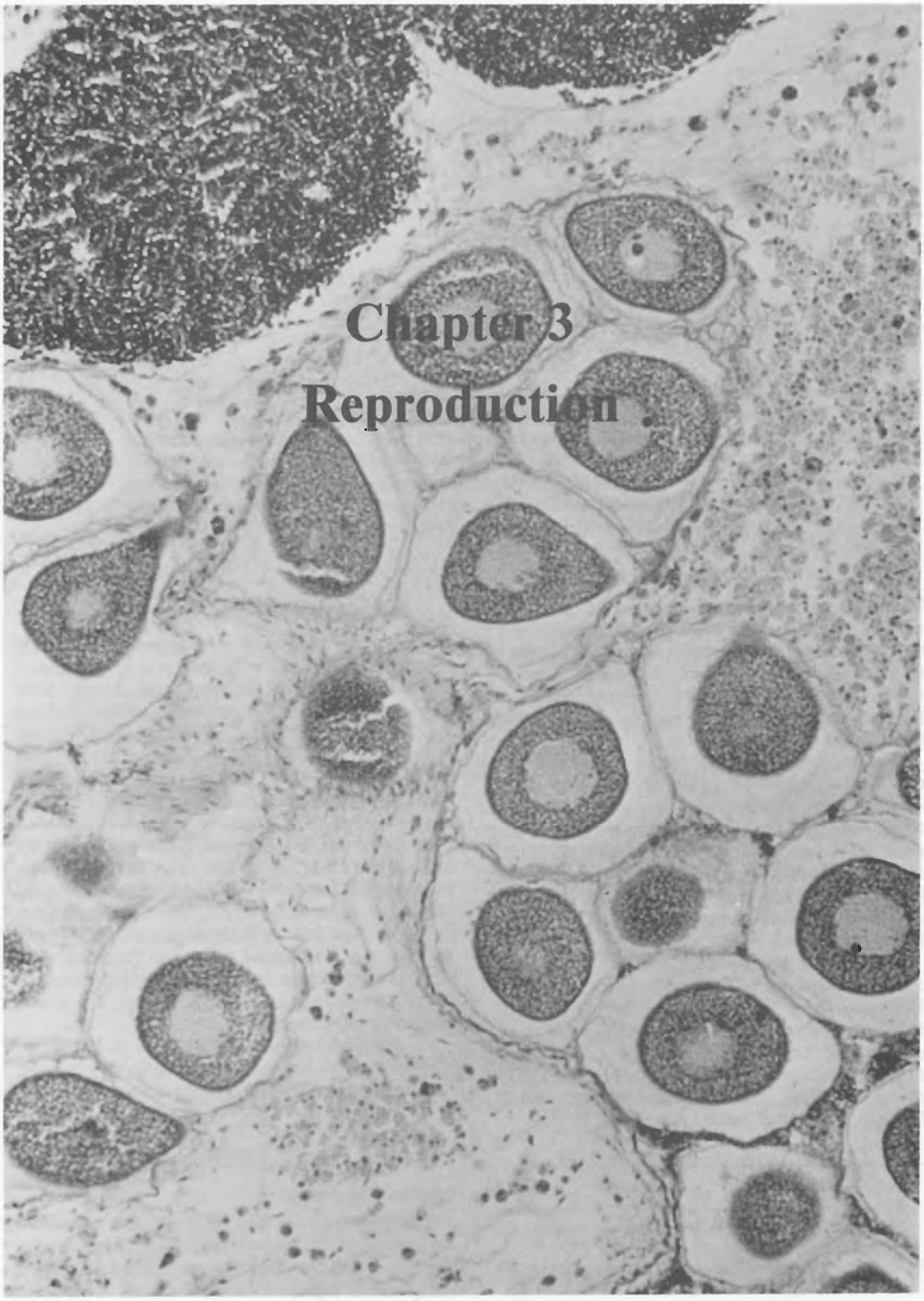
The apparent extreme and increasing rarity of the tevoro clam dictates that efforts should be directed at securing its survival, at least until its distribution and abundance are documented with more certainty. Attempts to establish a potential breeding nucleus at Makogai, where there are now facilities for the well-established extensive tridacnid culture techniques, have so far been unsuccessful. All five transferred clams have died and in only one case was the intact viscera recovered for taxonomic study.

These efforts will be continued, taking more account of the species deep-water habitat preference and aversion to strong sunlight. Once successfully established, every effort will be made to spawn the species there. Assuming the sharp valve edges are indicative of rapid growth, the species may prove more suitable for culture than *T. derasa*, an issue worthy of further investigation.

In the interim, scientists in other areas with stocks of *T. derasa* should be encouraged to investigate the possibility that the tevoro clam may still survive outside the limited known range in eastern Fiji.

Acknowledgments

The authors record their thanks to Mr Alfred Robinson of Suva for originally drawing the tevoro to their attention, to Mr Joeli Soko of Vatoa for the coordination of additional collections, to Dr Winston Ponder for the examination of material, to the Australian and Pacific Science Foundation for their support of efforts to ensure the survival of the tevoro, and of course to Tim Adams for his supporting role throughout this difficult work.



Chapter 3
Reproduction

Reproductive Periodicity and Morphometry of *Hippopus hippopus* and *Tridacna crocea*

C.C. Shelley* and P.C. Southgate**

Abstract

Reproductive periodicity of *Hippopus hippopus* and *Tridacna crocea* was examined using a gonad index. Both species showed an annual periodicity. A spawning season extending over several months was indicated for *H. hippopus*, whereas *T. crocea* appeared to have a more restricted spawning period. Seasonal changes in the external appearance of the gonads of both species are described. The morphometric relationships between wet mass, dry mass, shell length and shell mass are presented.

Most information on the reproductive periodicity of the Tridacnidae has come from observations of natural spawnings. Although some reports point to an annual reproductive cycle, with a pronounced spawning season (Braley 1984), in Palau individuals have spawned repeatedly throughout the year (Heslinga et al. 1984).

Braley (1984, 1986) has examined the reproductive cycle of *Tridacna gigas* by taking regular biopsy samples from the gonad of tagged clams. The first microscopic study on gonads of a giant clam was made by Stephenson (1934) on *Hippopus hippopus*, and results of the first histological study on *T. gigas* are presented elsewhere in this volume (Nash et al., This Monograph).

The use of a gonad index to follow the seasonal cycle of bivalves is a common practice (Sloan and Robinson 1984; Bricelj et al. 1987; Sause et al. 1987). By comparing the mass of the gonad to the mass of the somatic tissue, changes to the gonad throughout the year can be determined. In this study the gonad index and basic morphometry of *H. hippopus* and *T. crocea* are described.

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Methods

All *Hippopus hippopus* were collected from Little Pioneer Bay, and all *Tridacna crocea* from Pioneer Bay, Orpheus Island, in the Great Barrier Reef region. *Hippopus hippopus* were collected from June 1986 to June 1987, and *T. crocea* from October 1986 to December 1987. Clams were removed from their shells and the gonad dissected from other tissue. Observations on the appearance of the gonad were recorded. The digestive gland was removed from the gonad. The wet mass of the gonad and the total of the other tissues was recorded. All tissues were weighed into preweighed containers and dried at 60°C to a constant weight. The containers were then reweighed and dry mass calculated. Shell length and air-dried shell mass were also recorded. The number of clams used per month varied from 3–4 for *H. hippopus* and 4–5 for *T. crocea*. The gonad index was calculated as

$$\text{dry gonad mass/total dry mass} \times 100.$$

Relationships between wet weight, dry weight, shell mass and shell length were determined using linear regressions.

Results

Hippopus hippopus

The gonad index range (including standard deviations) of *H. hippopus* (Fig. 1) peaks between September and December, where upper values show the gonad to represent between 35 and 40% of the

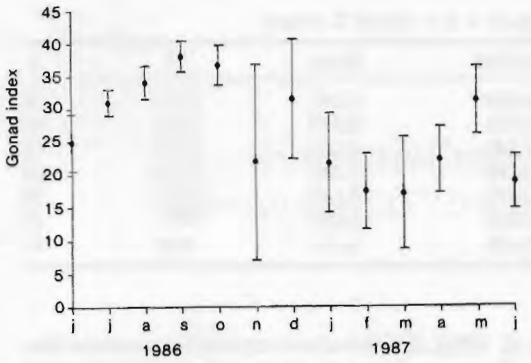

Fig. 1. The annual gonad index of *Hippopus hippopus* (bars indicate ± 1 SD).

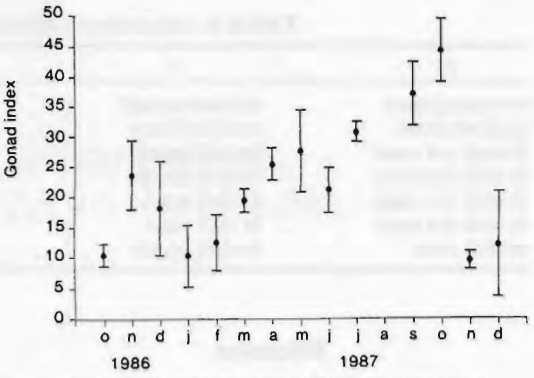

Fig. 2. The annual gonad index of *Tridacna crocea* (bars indicate ± 1 SD).

total body mass of the clam. The index in November and December shows a wide range, suggesting that whilst some clams are ripe others may have already spawned. The index declines to a low in March 1987 after which the relative size of the gonad increases. Although a decrease in the index in June may suggest a mid-year spawning, it is more likely the result of the small sample size and natural variation in gametogenesis.

Gross changes in the appearance of the gonads corresponded with changes in the gonad index. From April to May gonads were mostly flaccid. Moderately turgid gonads were noticed in June. In both June and July channels in the surface of the gonads were conspicuous. The gonads from August to October appear full and turgid. In November and December both turgid and flaccid gonads were present in the sample. Although the gonads examined from January to March were a mixture of moderately turgid to flaccid, when cut open the gonads were visibly loosely packed with material, compared to the very turgid gonads which were full and very firm.

Full turgid gonads were white-orange/white in colour, whilst flaccid gonads were generally offwhite with brown/yellow/orange/purple markings on the anterior end of the gonad. Basic morphometric relationships for *H. hippopus* are recorded in Table 1.

Tridacna crocea

The gonad index of *T. crocea* (Fig. 2) has three minor peaks and troughs during the year, the major peak occurring in October 1987, when the dry gonad mass was over 40% of the total dry body mass. There was a sharp decrease in November indicating spawning had occurred. Between the October and November samples (26 October) a mass spawning of the sample population was observed in the field (R. Braley, pers. comm.). A similarly low value in October 1986 indicates an annual periodicity of spawning. The slight increase in the index in November, followed by a further fall to January 1987, may indicate that a major spawning event can be followed by a second when conditions are suitable.

Observations on the appearance of the gonads indicate that in October 1986 and November 1987, at low points in the index, gonads are flaccid. In addition, gonads considered spent (November, December, January and February) had a more darkly pigmented gonad wall and an offwhite/grey appearance. In September and October, at the annual peak of the gonad index, gonads were turgid, cream in colour, and loose eggs were able to burst from any cuts in the gonad.

The morphometric relationships between tissues and shell are given in Table 2.

TABLE 1. Morphometric relationships ($y = a + bx$) of *Hippopus hippopus*.

y	*x*	Intercept	Slope	*R*	*n*
wet mass gonad	dry mass gonad	1.824	0.168	0.98	43
total wet mass	total dry mass	9.39	0.164	0.96	43
ln total wet mass	*ln* shell length	-6.959	2.35	0.79	43
ln total dry mass	*ln* shell length	-8.451	2.31	0.81	43
ln total wet mass	*ln* shell mass	0.354	0.764	0.80	43
ln total dry mass	*ln* shell mass	-1.352	0.761	0.83	43
ln shell mass	*ln* shell length	-7.092	2.648	0.85	43

TABLE 2. Morphometric relationships ($y = a + bx$) of *T. crocea*.

y	*x*	Intercept	Slope	*R*	*n*
wet mass gonad	dry mass gonad	-0.039	0.248	0.99	68
total wet mass	total dry mass	-0.303	0.219	0.98	68
ln total wet mass	*ln* shell length	-7.949	2.563	0.79	68
ln total dry mass	*ln* shell length	-10.265	2.731	0.78	68
ln total wet mass	*ln* shell mass	0.878	0.618	0.78	57
ln total dry mass	*ln* shell mass	-0.820	0.651	0.77	57
ln shell mass	*ln* shell length	-12.618	3.777	0.88	57

Discussion

The gonad index and observations of gonads, indicate that both *Hippopus hippopus* and *Tridacna crocea* exhibit annual reproductive periodicity at Orpheus Island. The sharp decrease in the index of *T. crocea* from over 40 in October to less than 10 in November suggests that the major spawning event is restricted to a small time period. However the more gradual decrease in the index of *H. hippopus* indicates a protracted spawning season from November to March. The relatively extended spawning season of *H. hippopus* at Orpheus Island has also been recognised through spawning trials, which have produced larvae between November and March over a number of years. This also agrees with Stephenson (1934) who found *H. hippopus* spawned between January and March at the Low Isles on the Great Barrier Reef.

The differences in the duration of the spawning season between the two species may be related to their relative spatial distribution on the reef. There is evidence to show that production of gametes by individual clams often induces a spontaneous spawning reaction in other clams of the same species (Gwyther and Munro 1981; Braley 1984; Heslinga et al. 1984). It is therefore reasonable to assume that as *T. crocea* occurs in dense aggregations in coral rock, it is likely that a large number of individuals will take part in that spawning event. In *H. hippopus* a spawning event may be more localised and will affect fewer individuals because of the more widely spaced reef flat distribution of this species.

The reproductive cycle of *H. hippopus* and *T. crocea* is being further defined by examination of seasonal changes in the biochemistry of the gonad. In addition biopsy samples and histology have been used to cross-validate results from the use of the gonad index (Shelley, unpublished data). The appearance of conspicuous channels, presumably haemal in nature, in June and July on the surface of the gonads of *H. hippopus* may indicate increased movement of materials associated with the onset of gametogenesis.

Acknowledgments

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A Histological Study of Reproduction in the Giant Clam *Tridacna gigas* in the North-Central Great Barrier Reef

W.J. Nash,* R.G. Pearson and S.P. Westmore*****

Abstract

Gonad samples were taken from *Tridacna gigas* on Arlington Reef, north-central Great Barrier Reef, at approximately monthly intervals between November 1978 and January 1980 in order to investigate the seasonality of reproduction. There was evidence of a major spawning between January and March 1979. Early spermatogenic stages were not seen in any of the samples, and early oogenesis in only two of the 10 samples. Presence of a higher proportion of spent or partly spent clams in November 1979–January 1980, compared to the same period 12 months earlier, suggests that spawning occurred earlier in the summer of 1979 than in the previous summer.

Testis and ovary development were mostly synchronous within monthly samples. In addition, reproductive stage was found generally to be the same in different parts of the gonad; the use of a single section from each clam is therefore considered adequate to accurately portray gonad condition.

THE success of giant clam culture relies on an ability to obtain ripe eggs and sperm when they are required. Artificial induction of spawning in *Tridacna gigas* has been achieved using an intragonadal injection of serotonin (Braley 1985; Crawford et al. 1986).

This paper describes the reproductive cycle of the largest giant clam species *Tridacna gigas*, determined from a histological study of the gonads of 129 clams sampled over a 14-month period, and helps clarify reproductive development and spawning periodicity of *T. gigas*.

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Tridacnid clams are protandrous simultaneous hermaphrodites, that is they first reach sexual maturity as males, then later develop ovaries which function simultaneously with the testes. Individual clams begin spawning sperm, then switch to egg release after approximately 30–60 min. Clams that release sperm do not invariably release eggs; in fact, egg release in wild populations has not been observed nearly as frequently as sperm release (Braley 1984a).

This study is unique because the gonad samples were taken at a time when interest in giant clams was not great, and concern about clam poaching throughout the Pacific was not widespread. Since that time, *Tridacna gigas* has been placed on the threatened species list of the International Union for the Conservation of Nature (IUCN 1983). Indeed, in some parts of its geographical range, such as the Philippines and Indonesia, *T. gigas* cannot be found in sufficient numbers to allow killing the clams for reproductive analysis (Alcala 1981, 1986; Brown and Muskanofola 1985). The clams used in this study were taken from reefs where they were abundant, and constituted only a small proportion of the total populations on those reefs.

Methods

Gonad Collection

The clams were sampled from Arlington Reef (16°44'S, 146°02'E) in the north-central Great Barrier Reef region between November 1978 and January 1980. The visceral mass containing the gonad was removed from 10 *Tridacna gigas* at each sampling period and preserved in 10% formalin. Further samples were collected in November and December 1979 from Hastings Reef (16°33'S, 146°02'E) and Michaelmas Reef (16°37'S, 146°00'E), respectively, to determine the size at which sexual maturity is reached. These clams were not included in the analysis of reproductive seasonality, since most were immature or male phase only. Details of collection dates and sites are given in Table 1.

Small pieces of preserved gonad tissue were excised and processed histologically, stained with haematoxylin and counterstained with eosin. For some samples, pieces of tissue were taken from both anterior and posterior parts of the gonad, to determine whether gonads are uniform with respect to their reproductive condition.

TABLE 1. Collection details of *Tridacna gigas* taken for reproductive analysis.

Date	Reef	Number of clams
2 Nov 1978	Arlington	10
19 Dec 1978	Arlington	10
24 Jan 1979	Arlington	10
5 Mar 1979	Arlington	10
3 Jul 1979	Arlington	11
3 Aug 1979	Arlington	10
11 Sep 1979	Arlington	10
9 Oct 1979	Arlington	10
12 Nov 1979	Arlington	10
26 Nov 1979	Arlington	10
5 Dec 1979	Hastings	8
20 Dec 1979	Michaelmas	10
10 Jan 1980	Arlington	10

Gonad Developmental Stages

The gametogenic stages recognised for ovary and testis are listed and defined as follows. This scheme is similar to that used for other bivalve species (e.g. Gallucci and Gallucci 1982; Braley 1984b).

Stage 0: Immature. No recognisable gonad tissue present. Connective tissue and granulocytes predominate.

Stage I: Early gametogenesis. **Female**: Ovarian follicles empty, and lined with developing oocytes. **Male**: Follicles empty, and lined with spermatogonia and primary and secondary spermatocytes.

Stage II: Mid-gametogenesis. **Female**: Ova beginning to fill the lumen of the follicle. Developing oocytes attached to the follicle wall. Ova small and elongate. **Male**: Spermatocytes predominate, with a small amount of spermatozoa in the follicle lumen.

Stage III: Late gametogenesis to ripe. **Female**: Ova mostly roundly polygonal, although some still elongate. In very ripe ovary, all ova round or elliptical, and densely packed. Follicle walls between individual ova thick and smooth, becoming thinner and more crenate in ripe ovary. **Male**: Testis mostly ripe spermatozoa, with spermatocytes lining the follicle. This lining decreases with increasing maturation, but almost no follicles are completely devoid of these. Acidophilic sperm tails form pink lines radiating from the centre of the follicle lumen.

Stage IV: Partly spent. **Female**: Spaces in ovarian follicles signify loss of ova through spawning. Follicle walls between ova very thin and crenate, or missing. Some ova undergoing cytolysis. **Male**: Spermatozoa missing from the central lumen of the testis follicle; this space sometimes filled with amoebocytes; or a general sparseness of spermatozoa through an entire follicle.

Stage V: Spent/regressing. Little or no recognisable gametic material. Interstitial connective tissue and amoebocytes predominate. **Female**: Follicles mostly empty or collapsed, although a few residual ripe ova may be present. Developing oocytes sometimes present on the follicle wall. **Male**: Often no sign of male gametes or testis at all; otherwise few residual strands of spermatozoa.

Since gonad maturation is a continuous process, there is no clear distinction between the developmental stages, making it difficult at times to assign a gonad to one stage or another. Late gametogenesis and ripe gonad were pooled as a single class (Stage III) since it was found that, in practice, many samples could not be unequivocally assigned to either category.

An overall developmental stage for both testis and ovary was ascribed to each gonad sample, based on an assessment of which gametogenic stage was predominant.

Results

There is a notable absence of early gametogenic stages of both testis and ovary. None of the clams contained early stage testis (except when later stages were also present in greater proportion), and very few had early stage ova (Fig. 1). The stages of gametogenesis are shown in Fig. 2.

A major spawning of both eggs and sperm apparently occurred between January and March 1979 (Fig. 1). Ninety percent of clams in January

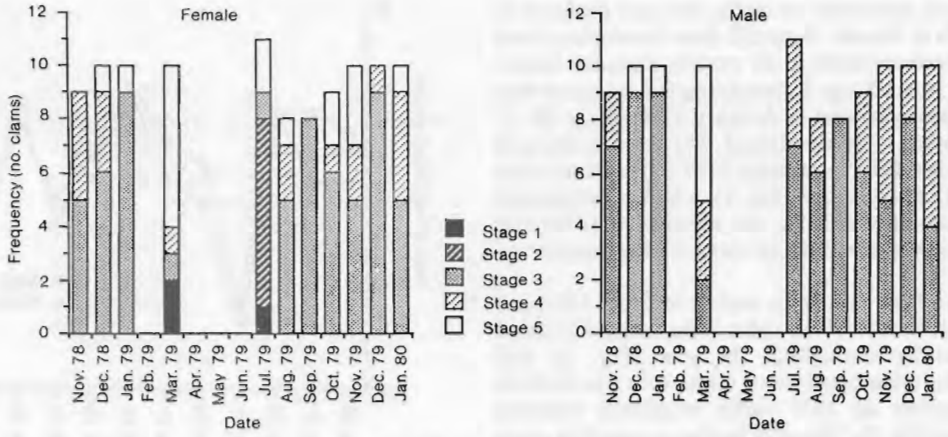

Fig. 1. Gametogenic stages of *Tridacna gigas* at each sampling period.

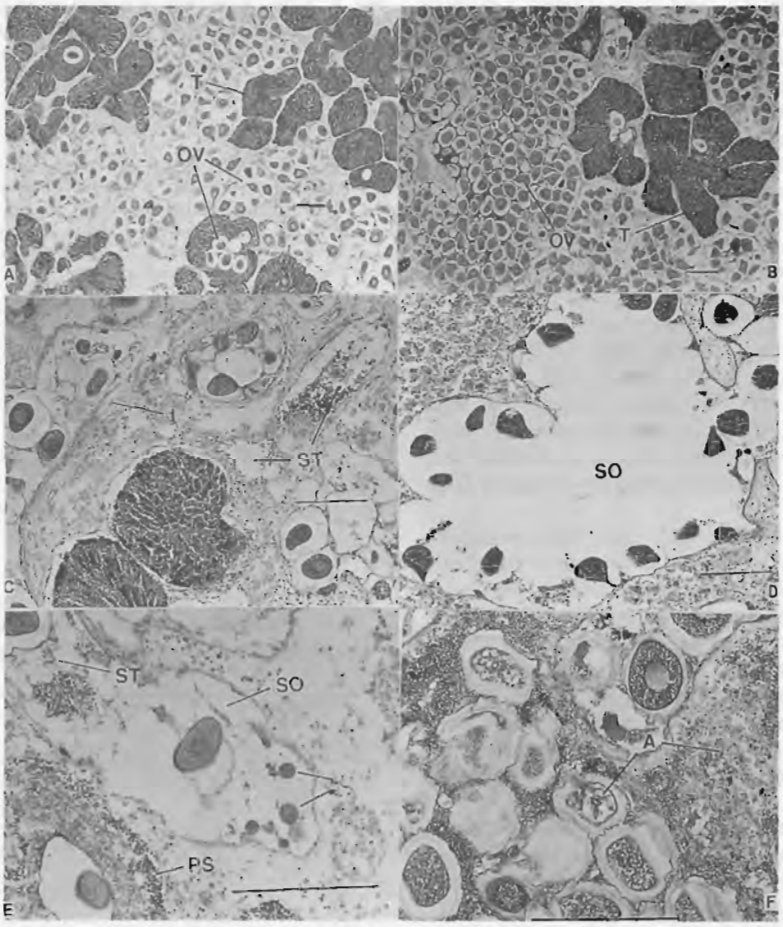

Fig. 2. Gametogenic stages of *Tridacna gigas*. A: Mid-development (note angular ova). B: Late development/ripe. C: Partly spent. D: Spent. E: Spent/regressing, with some early oogenesis. F: Amoebocytic cytolysis of testis and ova. Abbreviations: A = amoebocytes; I = interstitial connective tissue; O = oocytes; OV = ova; PS = primary spermatocytes; S = spermatozoa; SO = spent ovary; ST = spent testis; T = testis. Scale = 50 μm.

1979 had ripe ovary or testis; this had declined to 10–20% in March. Stage III (late developing/ripe) testis predominated in all months sampled except March, when Stage V (spent/regressing) tissue was most common, and in January 1980 (Stage IV — partly spent — predominant). The samples taken in November 1978 to January 1979 differ from those taken 12 months later (Fig. 1): a higher proportion of the clams sampled in the summer of 1979 were partly spent compared to those of the summer of 1978.

Apart from the sharp decline in Stage III (ripe) gonad in March 1979, there is no consistent trend of maturity throughout the year (Fig. 1). For example, the proportion of clams with ripe testis in the summer of 1979 varies erratically between samples (Fig. 1). This may be due to sampling error (too small a sample size), or it may reflect variation in spawning behaviour on a very localised scale.

Spermatogenesis and oogenesis showed approximately parallel development (Fig. 1). Within any one sampling period there is a range of gametogenic stages between individual clams, particularly for the female gonad, where individuals commonly range from ripe to spent (Fig. 1). This reflects variation in the time of spawning as well as spawning intensity.

To illustrate the similarity between the ripeness stage of testis and ovary at each sampling period, each gonad sample was assigned a gonad ripeness score for both tissues. Scoring was as follows: early developing = 2; mid-developing = 3; late developing/ripe = 4; partly spent = 1; and fully spent/regressing = 0, after the method of Dix and Ferguson (1983). A mean index of reproductive state for each sampling period was calculated for both testis and ovary. The testis and ovary exhibit very similar patterns of gametogenic development (Fig. 3).

Gonads from both anterior and posterior sections were taken, then examined to determine whether a single sample taken from a gonad is representative of the entire gonad. In the large majority of clams, both ovary and testis in anterior and posterior sections were at the same developmental stage (Table 2). Examples of asynchrony included Stage III (late developing/ripe) in one section and Stage V (spent) in the other, indicating that gametes may be released from only a portion of the gonad during spawning.

A comparison was then made of testis and ovary stages in individual gonad sections to determine whether the two sexes developed synchronously. In the majority of clams (69%) this was so (Table 3). For nearly all of the clams with asynchronous development, the stages were adjacent — for example, Stage III testis and Stage IV ovary.

Some clams contained ovary with both ripe and

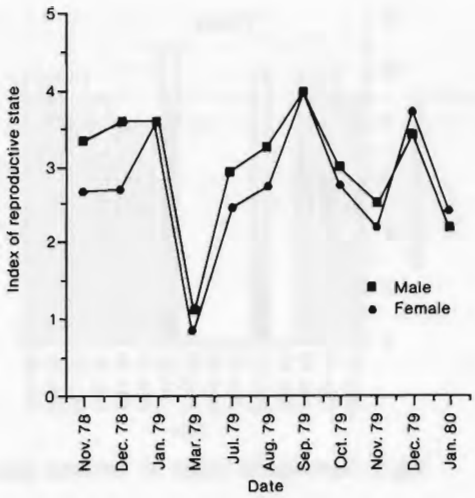

Fig. 3. Index of reproductive state of testis and ovary of *Tridacna gigas*. Samples with all spent clams would have an index of 0; all ripe clams would have an index of 4.

TABLE 2. Synchrony of gametogenesis and spawning between anterior and posterior sections of gonad taken from individual *Tridacna gigas*. See text for a description of the gametogenic stages.

Stage		No. of clams		
		Ovary	Testis	
III	III	38	42	Same stage
IV	IV	9	15	
V	V	11	4	
IV	V	2	4	Different stage
III	IV	1	5	
I	II	1		
III	V	1		

TABLE 3. Synchrony of gametogenesis and spawning between ovary and testis within individual *Tridacna gigas*. See text for a description of the gametogenic stages.

Stage		No. of clams	
Female	Male		
III	III	57	Same
IV	IV	7	
V	V	6	
IV	III	9	Different
V	IV	11	
III	IV	4	
II	III	4	
I	IV	2	
I	V	1	
II	IV	1	

regressing eggs, but with no sign of empty spaces to indicate spawning. The same was found for male gonad as well. The incidence of this as early as July, but extending through the summer months, suggests that there is continual replacement of gametes that is unrelated to spawning.

Examination of small clams sampled from Michaelmas and Hastings reefs in November and December 1979 (Table 1) revealed that the male phase of sexual maturity is reached in the size range 25–35 cm shell length (Table 4).

TABLE 4. Size at which male phase of sexual maturity is reached in *Tridacna gigas*.

Shell length (cm)	Immature	Male
20–24	4	0
25–29	2	2
30–34	1	3
35–39	0	3
40–44	0	1

Discussion

Since the clams had to be killed to obtain the gonad samples, it was not possible to monitor gametogenesis through time for individual animals. The sequence of reproductive development inferred in this study therefore assumes a degree of reproductive synchrony between clams. The developmental sequences which have been outlined above are an interpretation of what are analogous to photographic 'snapshots' of a continuous process.

Reproductive development can best be determined from a series of samples taken from individual clams. This can be carried out using gonad tissue removed by biopsy needle or syringe. Braley (1986) has described the reproductive cycles of *Tridacna gigas* and *T. derasa* using the biopsy technique, and his results agree broadly with those of the present study. As expected, more detail is available from the histological sections: the fine-scale structural relationships between ovary and testis could be discerned, and the persistence of primary spermatocytes in ripe testis was observed.

There is no evidence from this study that spawning of *T. gigas* takes place in a brief, well-defined interval. The presence of both ripe and partly spent animals for all of the summer months sampled suggests that spawning is protracted. Nevertheless, it was not expected that ripe gonad would be present in August and September, well before the onset of summer. Braley (1984a, 1986) and Crawford et al. (1986) found spawning of *T. gigas* to take place between November and February. Since samples were not taken between March and July, it is not possible to determine whether the late developing/ripe stages found in July and August are residues from the previous summer or the result of recent gametogenesis.

Similarly, amoebocytic cytolysis of gonad tissue as early as July was unexpected, but is consistent with the results of Braley (1986) who found, using the biopsy technique, that amoebocytes and regressing gonad tissue were to be found throughout the year. Braley concluded that the resorption of eggs and sperm not spawned in summer is a prolonged process which extends into the winter months. The results of this study are not inconsistent with that hypothesis. It should be noted, however, that the proportion of the samples in July–September exhibiting cell breakdown was not large, and was confined to female tissue. Other workers (e.g. Reddiah 1962) have also reported the presence of phagocytes in varying quantities in the gonad of bivalve molluscs throughout the year.

No sections were seen in which mature spermatozoa were not accompanied by primary spermatocytes. By contrast, fully ripe egg stages were not accompanied by early egg stages. From these observations it is tentatively concluded that egg and sperm development are different processes in *T. gigas*: Egg maturation is a coherent process whereby in any one breeding cycle maturation proceeds from primary oocytes to ripe eggs in an ordered chronological sequence culminating in spawning in mid-late summer. Testis development, on the other hand, is a continuous process in which both early and late stages are present simultaneously.

This difference is consistent with, and may account for, the observed differences in frequency of spawning of sperm and eggs. Observation of spawning of *T. gigas* in tanks shows that sperm release is much more frequent than egg release (Crawford et al. 1986). Similarly, *T. gigas* in the sea have been seen to release sperm far more frequently than eggs (Braley 1984a). This pattern may be widespread, as it is also reported for other marine invertebrate species such as the gastropod *Trochus niloticus* (Nash 1985).

In a study of reproduction in pectinid bivalves, Reddiah (1962) found that all the follicles of any one gonad of *Chlamys distorta* do not start spawning at the same time. Spawning is at intervals, and one group of follicles was found to spawn completely before another started. Subsequent spawnings were either from adjacent follicles or from ones more distant. In this study, individual sections of spawning *T. gigas* gonad generally contained both spent and ripe follicles. Since only a small proportion of *T. gigas* exhibited different

gametogenic stages in different parts of the gonad (Table 2), the use of only a single section from each clam will usually be sufficient to accurately determine reproductive condition. Consequently, the observation of Wada (1952) that, in *T. crocea*, testis tissue was often observed to be dominant toward the anterior end of the gonad, with ovarian tissue dominant posteriorly, is not supported for *T. gigas*.

Acknowledgments

The clams used in this study were collected by RGP and staff of the Northern Fisheries Research Centre, Cairns. Histological processing of the gonad tissue samples was also carried out there. Microscopic analysis of the sections was carried out by WJN while employed on the ACIAR Giant Clam Project at James Cook University.

An Improved Gonad Biopsy Technique for *Hippopus hippopus*

C.C. Shelley* and R.G.B. Reid**

Abstract

A standard biopsy technique for clams of the family Tridacnidae resulted in high mortalities when used on *Hippopus hippopus*. Postmortem anatomical studies showed that mortalities were caused by puncture of the pericardium, resulting in the loss of haemal fluid. Similar damage to the digestive gland and style sac may also have contributed to mortalities. An improved biopsy technique is described which takes into account the anatomical arrangement of the gonad in relation to the visceral mass.

REPEATED gonad biopsy samples have been taken routinely from *Tridacna gigas* and *T. derasa* (Braley 1984; Crawford et al. 1986) to determine ripeness of gonads and to study reproductive periodicity.

Braley (1984) described a biopsy technique, based on Gwyther and Munro (1981), which used a hypodermic needle with a plastic plunger to extract gonadal tissue. The needle is inserted vertically down into the gonad through the mantle, entering the gonad several centimetres anterior to the exhalent siphon, to one side of the medial axis of the clam.

At Orpheus Island Research Station, the common procedure has been to use a human biopsy needle with 152 mm cannula, 20 mm specimen notch (Crawford et al. 1986), and to enter the gonad at approximately 45 degrees to the vertical at the point indicated by Braley (1984). This technique was used to take biopsy samples from 39 *H. hippopus* in Pioneer Bay, Orpheus Island, in May 1986. Of the 39 clams sampled using the standard Orpheus Island technique, eight (20.5%) died the next day. Biopsy samples were taken monthly from tagged clams. Mortalities during the year were replaced so that approximately 30 clams were biopsied each month.

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To determine the cause of death, postmortem examinations of dead clams were undertaken when mortalities occurred and tissue was available for examination.

Methods

Recently dead *Hippopus hippopus* were removed from their shells and examined. If not examined immediately clams were stored in 10% formal saline.

One *Hippopus* about to be killed for other reasons was biopsied so that a live recently biopsied clam could be examined.

An anatomical study of the visceral mass of *H. hippopus* was undertaken from the dead clams so that an improved biopsy technique could be designed.

Results

The freshly biopsied clam, once the mantle had been removed showed pericardial fluid being forcefully pumped from a puncture wound in the pericardium. The wound was caused by the biopsy needle being pushed through the mantle into the gonad, and in the process puncturing the pericardium. There was also a hole in the pericardium from an earlier biopsy sample that had been plugged with new tissue. Of the four other *Hippopus* examined, all had holes in the pericardium.

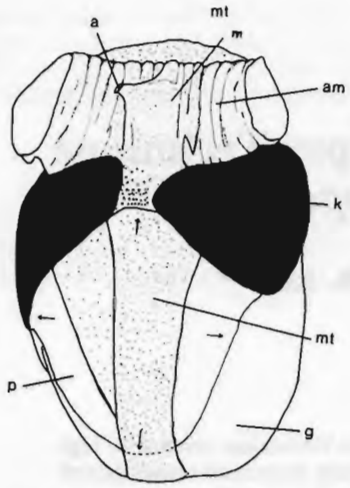

Fig. 1. The visceral mass of *Hippopus hippopus* viewed from the clam's dorsal surface. The extent of the pericardium shows that biopsying from the dorsal surface is almost certain to puncture the pericardium.

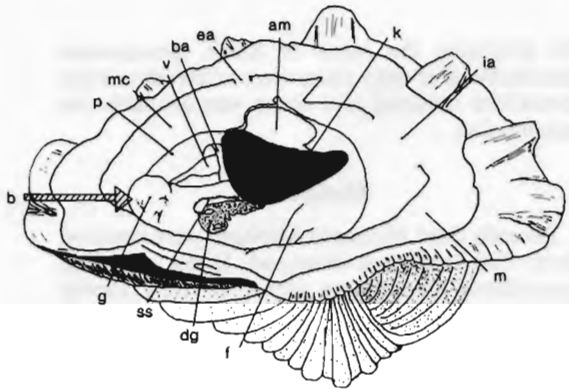

Fig. 2. The cut-away internal anatomy of *Hippopus hippopus*. The gonad has been cut in half from the apex (arrow head) to just before the foot to reveal the digestive gland. The pericardium has been cut open to reveal its contents (auricles not included). Ctenidia have been omitted from drawing. The arrow indicates the position of approach to the gonad for a biopsy sample.

Key to Figures: a = anus, am = adductor muscle, b(arrow) = correct direction for insertion of biopsy needle, ba = 'bulbus arteriosus' (MacDonald 1854) or 'aortic bulb' (Lacaze-Duthiers 1902), ea = exhalent siphon, f = foot, dg = digestive gland, g = gonad, ia = inhalent siphon, k = kidney, m = mantle, mc = mantle cavity, mt = mantle tissue, p = pericardium, ss = style sac, v = ventricle (of heart), fine arrows in Fig. 1 indicate extent of pericardium.

The pericardium of *Hippopus* extends almost to the anterior end of the visceral mass, almost covering the dorsal surface of the gonad (Fig. 1). The pericardium contains the muscular 'square-shaped' ventricle (Lacaze-Duthiers 1902) and two auricles of the heart (Fig. 2).

In the centre of the gonad lies the large digestive gland, together with the style and style sac. The distance from the anterior end of the gonad (opposite end to the kidney) to the internal digestive gland was 50 mm in a gonad 175 mm in length. As a biopsy needle with a 150-mm cannula was used, the potential to puncture the digestive gland and style sac in addition to the gonad is clear. Indeed some biopsy samples contained digestive gland material.

Improved Biopsy Technique

A method that avoids puncturing the pericardial chamber requires insertion of the biopsy needle horizontally from the anterior of the mantle, angled to one side of the medial axis of the clam, thus entering the gonad without passing through the pericardium (Fig. 3). As a biopsy needle is pushed through the mantle and then the gonad wall, two distinct releases in pressure on the needle are felt. As soon as the second 'release' is felt, indicating the needle is through the gonad wall, the specimen notch should be pushed forward and the sample then cut. Restricting the depth of insertion of the biopsy needle minimises the potential for damage to the digestive gland-style sac complex.

Discussion

Puncturing the pericardium would seem highly likely using either of the biopsy techniques developed for *Tridacna gigas* for *H. hippopus*. This is because the pericardium almost entirely covers the dorsal surface of the gonad (where it is not covered by the kidney), where the biopsy needle or syringe is inserted. Lacaze-Duthiers (1902) noted the relatively greater width and decreased height of the visceral mass of *H. hippopus* compared to *Tridacna*, and the relatively larger size of the pericardium. Differences in relative and actual anatomical size between the larger tridacnids and *H. hippopus* can in part explain the mortalities recorded.

In addition to puncturing the pericardium, damage to the digestive gland-style sac complex inside the gonad could have major metabolic implications which may have resulted in mortalities.

When considering the arrangement of the visceral mass, many more *H. hippopus* must have had their pericardia punctured by the original biopsy technique than those that died. This may be explained by the fact that some punctures of the pericardium may occur without puncturing the heart

itself, as the chamber of the pericardium does appear large compared to the size of the heart within it. The puncture wounds may readily heal (as noted in the results), though it would seem unlikely that a puncture of an auricle or ventricle could be closed when they are pumping under pressure.

The improved biopsy technique reduced mortalities of regularly biopsied clams for 20.5% to a mean of 5.5% per month. Such losses are still high compared to mortality rates for biopsying *T. gigas* and *T. derasa* (Braley 1986) and unacceptably high considering the scarcity of giant clams in some regions. It is important that the risk of mortalities from biopsy sampling be understood, especially when one is working with the rare *H. porcellanus*, which presumably is anatomically similar to *H. hippopus*.

Acknowledgments

This work was partially funded by the Commonwealth Scholarship and Fellowship Plan, and the ACIAR-funded Giant Clam Mariculture Project.

Reproductive Condition and Season of the Giant Clams *Tridacna gigas* and *T. derasa* Utilising a Gonad Biopsy Technique

R.D. Braley*

Abstract

Hypodermic extraction of gonadal material was used to follow reproductive condition in discrete populations of *T. gigas* and *T. derasa*. The optimal reproductive season for *T. gigas* was October-February but more limited in *T. derasa* from September/October to November/December. Preliminary work using this technique at various reefs supports this seasonality of reproduction in these two species. The mean hypodermic extract volume (MEV) was a good indicator of gonad condition and supported the results of microscopic examination of the biopsy samples. A spawning of eggs in the Michaelmas Cay population of *T. gigas* in November/December 1984 was evidenced by the MEV index and indices derived from microscopic examination.

Simultaneous hermaphroditism was confirmed in 44–100% of biopsied *T. gigas*, but the monoecious condition as well as 'resting' condition ('neither sex') were present in small to moderate proportions over a 2-year period. On the other hand, simultaneous hermaphroditism was found in 0–28% of biopsied *T. derasa*, while the monoecious condition and resting condition were more prevalent throughout sampling periods. June-October was the only period of the year when less than 65% of biopsied clams were in resting condition.

Reproductive studies on tridacnid clams which involved examination of gonad samples from natural populations have been very limited (Stephenson 1934; Braley 1984). Stephenson (1934) found ripest gonads in *Hippopus hippopus* from mid to late summer (January through March) at Low Isles. Braley (1984) used a hypodermic extraction technique first suggested for clams by Gwyther and Munro (1981) and found the optimum reproductive season for *T. derasa* was austral spring to early summer while early to midsummer was optimal for *T. gigas*. Of the sampled clams during these reproductive periods, a significant number of individuals were also in the 'resting' or 'regressive' stages of gonad condition.

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In this paper, reproduction in natural populations of *T. gigas* and *T. derasa* was investigated using the hypodermic extraction technique. Michaelmas Cay and Myrmidon Reef were the sites chosen to sample the same population of individual clams over periods of 24 and 22 months, respectively. However, most of the data in this paper will relate to the Michaelmas Cay site. This method is briefly compared with a histological study of the gonads of killed *T. gigas* (Nash et al., This Monograph).

Methods

The gonad biopsy technique described by Braley (1984) for use with tridacnid clams was used in this study. A 10-cm hypodermic needle was used to extract a small amount of gonadal tissue from clams (Fig. 1). Incorrect aim could pierce the kidney,

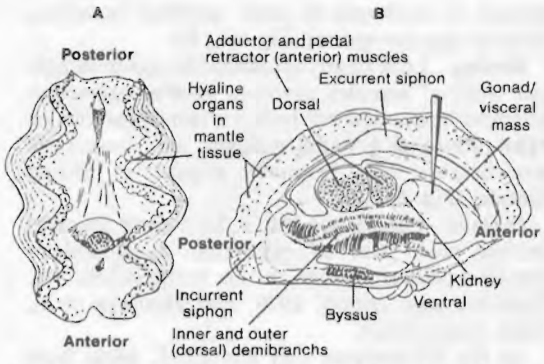

Fig. 1. *Tridacna gigas*, dorsal view (A), and *T. derasa* looking from the removed right side (B) (modified after Stasek 1962). Pointers show area and angles from which biopsies of gonadal tissue were taken.

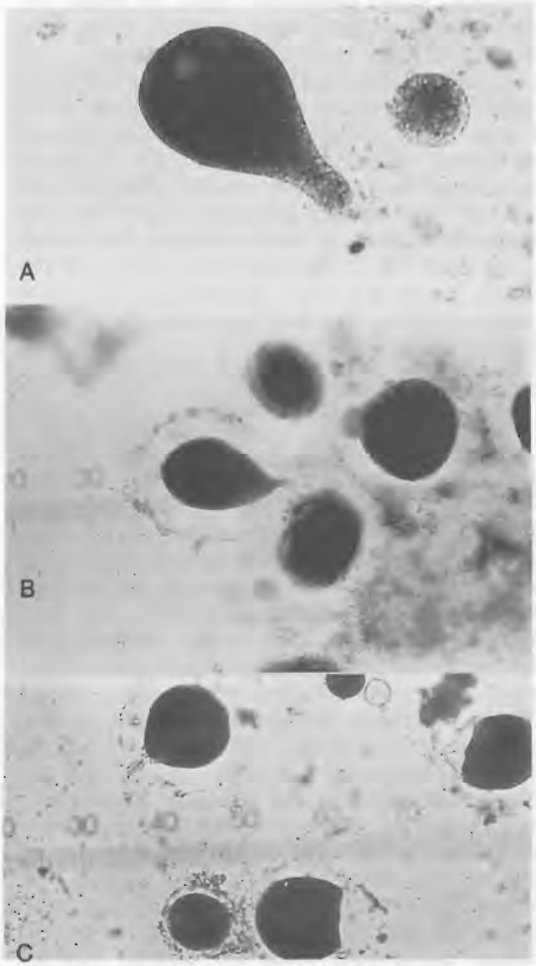

Fig. 2. Developing to Ripe (A–C) ova in hypodermic extract samples.

resulting in a contaminated sample and possible damage to the clam. Methylated spirits was used to sterilise needles and syringes between use on clams. The extracted gonadal material was preserved in 2% buffered formalin followed by microscopic examination. Amounts of sperm in the samples were ranked arbitrarily. Egg size determinations were made from means of 15 randomly chosen eggs using an ocular lens vernier on a compound microscope. Stages of gonad condition recognised for eggs were:

Developing Eggs up to 110 μm, generally various sizes in a progressive state. Some developing eggs have a distinct peduncle, which is the area of attachment to the follicle wall. The chorion layer is intact (Fig. 2).

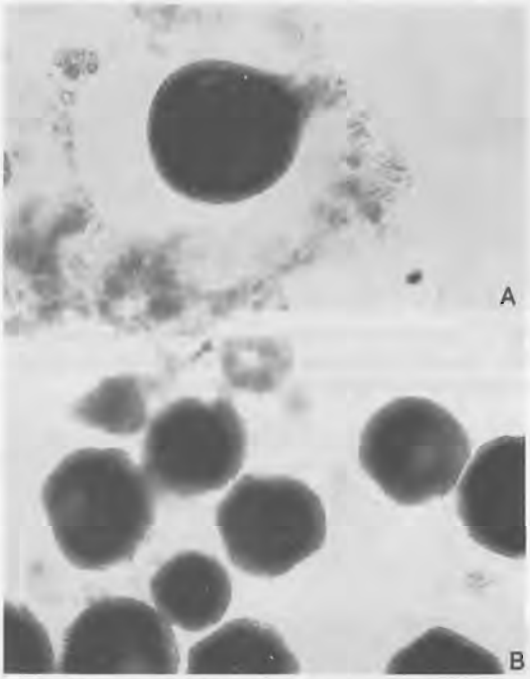

Fig. 3. Ripe ova (A–B) in hypodermic extract samples.

Ripe Eggs from 110 μm and larger, vitellogenesis complete (ova cytoplasm filled with yolk), easily ruptured (Fig. 3). These ova have intact chorion layers although some are occasionally ruptured out of the chorion, possibly due to the movement through the syringe needle during extraction. Often large numbers of ripe ova will be somewhat polygonal in shape due to the dense packing inside ovary follicles (Fig. 3B).

Regressive (post-spawning condition) Eggs any size but degenerative. Chorion layers often damaged or sometimes not present, phagocytic amoebocytes

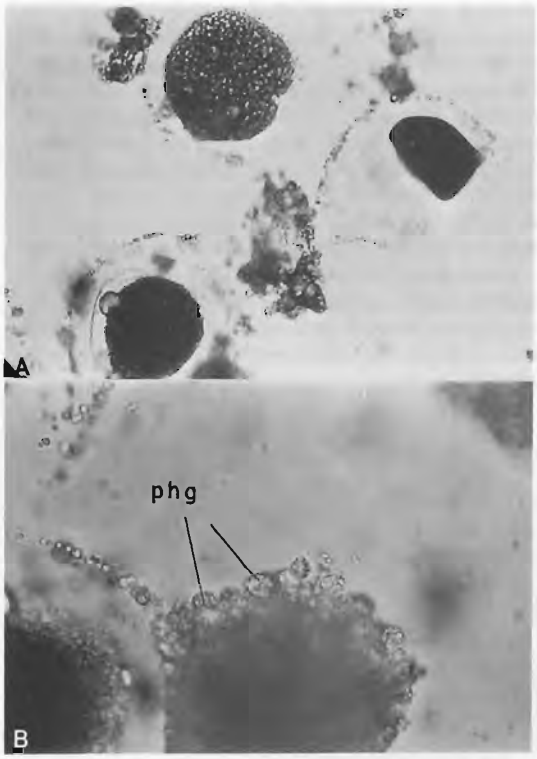

Fig. 4. Regressive ova in hypodermic extract samples (A, 100×, B, 200×), showing phagocytic amoebocytes (phg) on surface of a residual regressive ova.

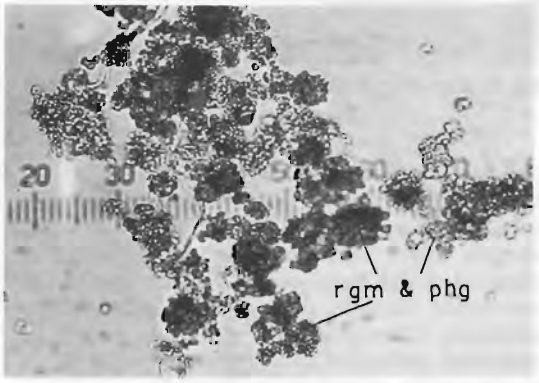

Fig. 5. Resting ova in hypodermic extract samples. Both residual gonadal material (rgm) and phagocytic amoebocytes (phg) are present in small amounts in this stage. 100×; 1 scale unit = 10 μm.

present in moderate to large numbers resorbing residual eggs (or sperm) (Fig. 4A, B).

Resting Lack of any recognisable eggs in sample (all 'resting' samples involved several extraction attempts by hypodermic to be certain of the lack of eggs). Residual gonadal material and phagocytic amoebocytes were normally present in resting samples (Fig. 5).

In Palau, 110 μm and 106 ± 1 μm were found to be the mean size of eggs that developed to metamorphosed larvae after fertilisation (N. Beckvar, pers. comm. 1979, and Heslinga et al. 1984, respectively).

At the Michaelmas Cay site 23 *T. gigas* were tagged and biopsied from January 1984 through December 1985. Additionally, five randomly chosen clams within the study site were sampled each month with the group of 23 regulars to act as controls for the effect of the biopsy technique upon gonad condition. From September 1985, 15 clams (10 regulars + 5 random) were sampled. Visits were made by diving or tourist boats from Cairns.

At the Myrmidon Reef site, 24 *T. gigas* and 13 *T. derasa* were tagged and biopsied. An additional five *T. gigas* and five *T. derasa* were randomly chosen for biopsy samples. Visits were made quarterly throughout the year from January 1984 through October 1985 aboard scheduled trips with the Australian Institute of Marine Science. By the end of the study one *T. gigas* and five *T. derasa* of the regular group had died, presumably due to the biopsy sampling. The final sampling was of seven *T. gigas* and seven *T. derasa*.

Results

The number of ripe *T. gigas* which were found at each sampling date at Michaelmas Cay is shown in Fig. 6. It is notable that the regressive stage was predominant throughout most of the year, including the October–December 1984 period. Developing and/or ripe stages were only present in January–February 1984, October–December 1984 and September–December 1985. Partial developing or ripe biopsy samples were present in some clams that were predominantly regressive stage clams. Numbers of clams with partial developing or ripe condition (indicated by an asterisk) were highest during the last quarters of 1984 and 1985 (Fig. 6). The resting condition was present at all sampling periods, but was minor when developing and ripe stages were present. No evidence of spawning of eggs was found in individual clams during early 1984 or late 1985. During this time the mean hypodermic extract volume (MEV) of biopsy samples did not change dramatically from the optimal summer reproductive season (Fig. 7). On the other hand, the decrease in MEV in November and December of

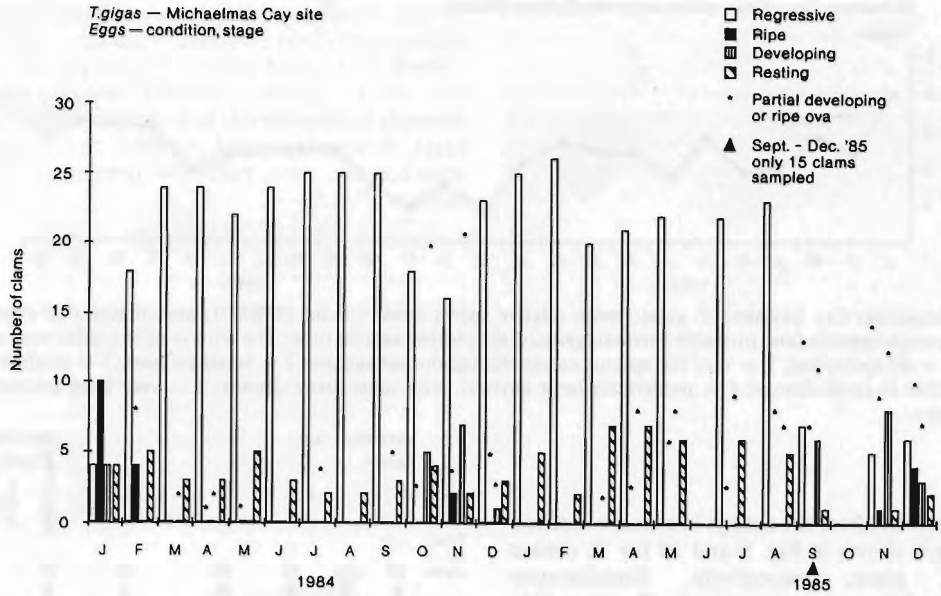

Fig. 6. Michaelmas Cay site: stages of egg condition for *T. gigas* over a 24-month period.

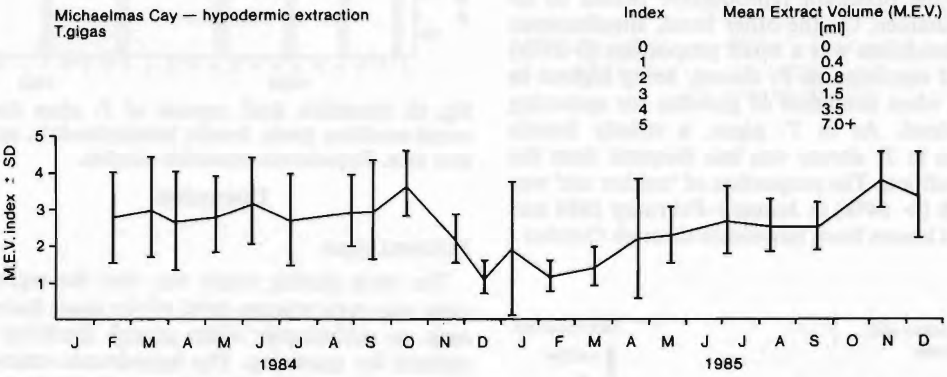

Fig. 7. Michaelmas Cay biopsies: *T. gigas*, mean hypodermic extract volume (MEV) index ± SD is plotted against time. n = 27 or 28 on all sample dates except for October 1985 (n = 14), November and December 1985 (n = 15 each).

1984 (Fig. 7) indicated that a spawning of eggs occurred by most of the regularly sampled clams and rapid regression occurred to residual ova by January 1985 (Fig. 6).

The mean relative sperm density index (MRSDI) indicates that a major release of sperm occurred throughout most of the sampled population in November and December 1984 (Fig. 8). Sperm would have been nearly completely released prior to the egg-release, as has been noted from spontaneous spawning in pools (personal observations 1984–85, and J.S. Lucas, pers. comm. 1986).

No significant differences were found in sample volume between regularly sampled and randomly sampled clams (Wilcoxon's signed-ranks test, $P > 0.1$).

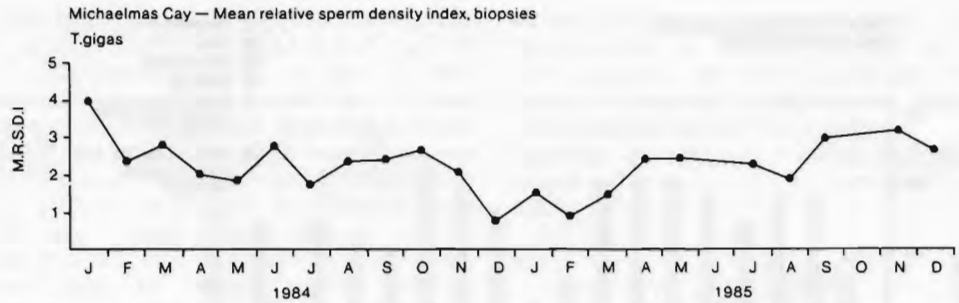

Fig. 8. Michaelmas Cay biopsies: *T. gigas*; mean relative sperm density index (MRSDI) and numbers of clams showing spermatogenesis (and probable spermatogenesis) are plotted against time. The criteria of the index were as follows: 0 = no sperm [ns]; 1 = very few sperm present throughout subsample; 2 = small amount; 3 = moderate amount, often in small clumps; 4 = moderately large amount, with some dense clumps; 5 = very large amount, dense clumps.

At Myrmidon Reef the change in sexual condition over time is shown in Fig. 9 and 10 for *T. derasa* and *T. gigas*, respectively. Simultaneous hermaphroditism was common in *T. gigas* (44–100%) and a strictly female condition was less frequent than the male condition. The smallest proportion of 'neither sex' was in October 1985 and highest proportion in June 1985; these data also indicate the optimum reproductive period to be spring-summer. On the other hand, simultaneous hermaphroditism was a small proportion (0–28%) of sexual condition in *T. derasa*, being highest in October when condition of gametes for spawning was optimal. As in *T. gigas*, a strictly female condition in *T. derasa* was less frequent than the male condition. The proportion of 'neither sex' was very high (> 64%) in January–February 1984 and 1985 and lowest from midwinter through October.

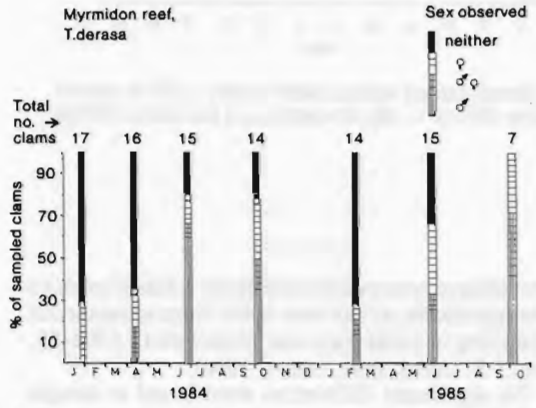

Fig. 9. Myrmidon Reef: percent of *T. derasa* showing sexual condition (male, female, hermaphroditic, neither) over time. Hypodermic extraction samples.

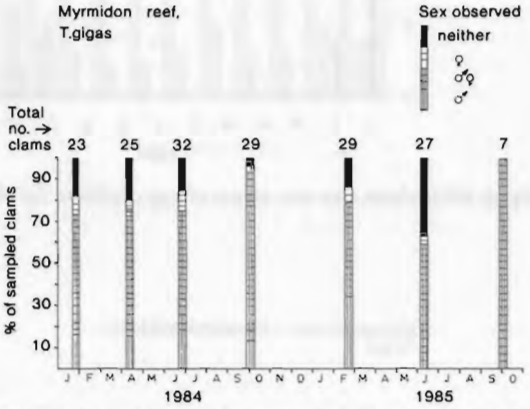

Fig. 10. Myrmidon Reef: percent of *T. gigas* showing sexual condition (male, female, hermaphroditic, neither) over time. Hypodermic extraction samples.

Discussion

Tridacna gigas

The most glaring result was that the regressive stage was predominant most of the year, including early to midsummer when gonad condition was optimal for spawning. The hypodermic extraction technique may tend to suck loose regressed gametes from within follicles in the gonad, thus biasing the outcome towards the regressive stage. However, other clear examples of developing, ripe and resting stages were found in individuals indicating that the hypodermic extraction technique does give a true picture of the state of the gonad. Braley (1984) found that in early to midsummer the gonad condition of *T. gigas* was optimal for spawning. Biopsies were taken from different individuals and sites at different times. Higher proportions of sampled clams were resting in that initial survey than found amongst the discrete populations sampled here. A finer eye for regressive ova in small volume samples may explain the increased proportion of the regressive stage over preliminary samples collected

in Braley (1984). The mean hypodermic extract volume was a good indicator to follow gonad condition and it supported the results of the microscopic examination of gonadal material. Likewise, the volume of biopsy samples (with human biopsy needle) taken from *T. gigas* at Orpheus Island was the favoured indicator of gonad condition (ACIAR 1986). There, egg shape and egg case type were indicated as poor criteria for predicting ripe gonads in clams.

Gonad samples obtained from *T. gigas* over a 12-month period (from R. Pearson, Queensland Fisheries Service) have been prepared and examined by W. Nash (Nash et al., This Monograph). Ripe eggs were found from September to March–April, but the optimum period was November–January. Gametogenesis began in May–July and occurred only once during the year. Partial spawnings were usual. My hypodermic extraction technique supports these findings but the evidence of gametogenesis was not apparent until August–October with my technique.

Tridacna derasa

Contrary to the discrepancies in resting and regressive stages between *T. gigas* in Braley (1984) and this work, *T. derasa* showed a high proportion of the resting stage in both the present work and Braley (1984). October was the optimal time to look for developing or ripe ova in this work, though October, December and February were indicated in Braley (1984) over several reefs at different times. In *T. derasa*, if spawning occurred it would be complete or else the regression of residual gametes may be rapid.

Hermaphroditism was shown by Grobben (1898) in *T. elongata (maxima)*, Stephenson (1934) for *H. hippopus* and Wada (1952) for *T. crocea, T. squamosa, T. serrifera (derasa)* and *H. hippopus*. Wada (1952) found protandrous hermaphroditism to be the rule. For *T. serrifera (derasa)* larger than 30 cm shell length, Wada found three of seven clams to be hermaphrodites, three males, and one female. Histological sections of gonad from a small number of *T. derasa* found either testes or ovaries but no sign of simultaneous hermaphroditism (ACIAR 1986). In the present study simultaneous hermaphroditism was present but less frequently in *T. derasa* than *T. gigas*. It became most apparent during October, the optimal reproductive period for *T. derasa*. The female condition in *T. gigas* was a little less common than the male condition but the hermaphrodite condition dominated throughout the year.

Reproductive Strategy

The natural release of sperm by *T. gigas* is predictable in early to midsummer months but natural egg release has not been observed in nature (Braley 1984). An egg-catching device (Braley 1984, 1986) was largely unsuccessful in collecting spawned eggs, indicating that egg release did not follow sperm release in most cases. Likewise for clams in captivity sperm is released more readily than eggs (Heslinga et al. 1984). *Tridacna gigas* may annually release sperm triggered by temperature increase or the chemical presence of other clams or eggs. Unlike sperm release, specific environmental cues may be required before release of eggs occurs. Phytoplankton densities which would be beneficial to high survival of larval and settled clams may act as one cue. Himmelman (1975, 1980) has shown natural phytoplankton-induced spawning of temperate invertebrates. Birkeland (1982) suggests that if high rainfall affects phytoplankton blooms as a result of the increased nutrients from terrestrial runoff, then there would also tend to be a seasonality in spawning of tropical marine invertebrates as there is in temperate regions. Cues such as this may occur in certain years only, resulting in sporadic spawnings. Clams which may not spawn eggs during one reproductive season could hold these eggs in various states of regression for months. This residual gonadal material may be resorbed as is typical in tropical oysters after spawning (Braley 1982) or possibly converted more directly into new gametes as earlier suggested.

The high population densitities of *T. gigas* and *T. derasa* on certain reefs (Braley, in press) may form a disproportionately large part of the reproductive population for extensive areas of the Great Barrier Reef. The relatively low densities of these clams on most reefs surveyed (Braley, in press) suggest that successful fertilisation of eggs would be unlikely in these localities. Why dense populations occur only at certain reefs is unknown. Perhaps gyres such as described in Palau (Johannes 1978) return larvae to these reefs, or sporadic and spatially random high-density recruitment occurs on a given reef. These relatively long-lived animals could afford to wait for optimum conditions for successful survival and settlement of their larvae. This would favour a visible *K*-strategy of reproduction in a potential *R*-strategist animal. Low levels of recruitment (Yamaguchi 1977; Pearson 1977; Braley 1986) are supportive evidence for this strategy.

Acknowledgments

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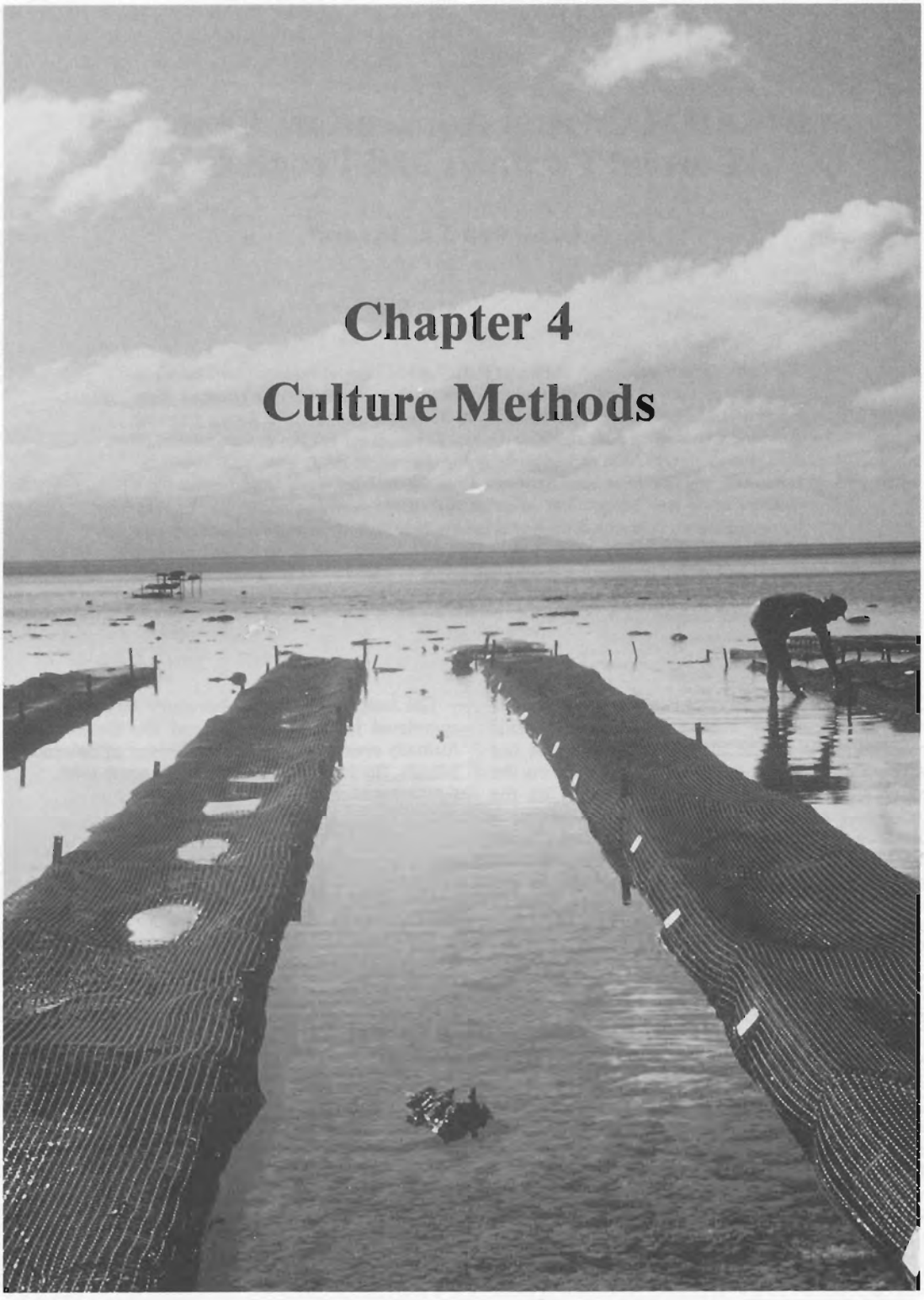

Chapter 4
Culture Methods

ICLARM Coastal Aquaculture Center: Current Facilities and Progress

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Abstract

The Giant Clam Hatchery component of the ICLARM Coastal Aquaculture Center has been constructed and is now operational. The facilities are described. *Tridacna gigas* broodstock collected from two sites within Solomon Islands have shown frequent spawning activity since their arrival at the site. The facilities and equipment installed to date at the hatchery have proved suitable for the culture of *T. gigas* and 75 000, 3-month-old juveniles have been harvested from the first spawning, and further large numbers of 1- and 2-month-old juveniles are visible in the settlement tanks. The economical fabric raceways developed at the site have proved suitable for the rearing of juvenile *T. gigas*. At the current level of spawning activity and juvenile production it should be possible to achieve a production target of 250 000 one-year-old clams/year with the current facilities. Expansion of the existing system will be easy and will give a considerable increase in output.

Over the past decade a considerable amount of research effort has been expended by various research teams on the culture of giant clams, but very little information has been published on the economic viability of clam cultivation or on the technical aspects of different culture options, both of which are crucial aspects of the eventual success or failure of giant clam farming. To address these a giant clam hatchery has been developed at the ICLARM Coastal Aquaculture Center (CAC) which is situated 25 km west of Honiara, the capital of Solomon Islands. It is the first component of the CAC and is being developed in collaboration with the Fisheries Department of the Government of Solomon Islands and the Guadalcanal Provincial Government. The agreement to establish the CAC was finalised on 4 June 1986 and the acquisition of the site completed and site clearance begun in October 1986. The first broodstock arrived on site in July 1987, and the aquaculture complex became operational in September 1987. Spawnings of *Tridacna gigas* occurred in November and have since recurred on a monthly basis, except for December.

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The hatchery/office/laboratory building was completed in January 1988 and the Center was formally opened by the Prime Minister of Solomon Islands, the Hon. E. Alebua, on 12 April 1988.

Description of Site and Facilities

Site

The 4.8-ha site lies between the main coast road and the sea, 25 km west of Honiara. The property is flat and well drained. A freshwater spring emerging into a small pond drains into the sea some 100 m from its western boundary. Formerly part of a coconut plantation, the lease on the area was bought back by the Government of Solomon Islands and leased to ICLARM for a period of 50 years. The 450-m shoreline has a fringing reef, and a lease has also been acquired over the seabed to 100 m offshore. The maximum tidal range is 1.2 m with a mean of approximately 0.6 m. Salinity is high and visibility generally greater than 10 m except during occasional rough conditions.

Facilities

Two caretaker cottages, a hatchery/laboratory/office building and a manager's house have been

completed. A residential block of four units is currently under construction, one unit has been finished and two others will be complete by mid 1988.

An existing brick generator shed has been refurbished, and a small brick pumphouse constructed close to the shoreline to house the seawater pumps.

Intake There is currently one 72 m long 110 mm diameter intake line permanently installed across the reef flat. It is secured with starpickets and galvanised wire and concrete-filled sacks. The end of the intake lies approximately 4 m below the water surface at ELWS, and is fitted with a 4-inch (10-cm) BSP screw fitting adaptor connecting with a short length of 100-mm PVC pressure pipe and thence to the intake screen. The stainless steel (316) intake screen is a 2.5 m long 5-inch (12.5-cm) tube with a continuous winding spaced to give an intake size of 150 μm. Following initial problems with pitting of the screen, a sacrificial zinc anode has been attached by a battery cable and stainless jubilee clip to the neck of the screen. No corrosion of the screen has been seen in the three months since the fitting of the anode.

The large size of the intake line significantly reduces the friction loss component of the suction head ($<$ 0.2 m when using the 2-inch (5-cm) pump) and allows an immediate expansion of pumping capacity without the need to install a new intake line. A 100 m long 65 mm diameter polyethylene pipe is also available for emergency use if required.

Pumping A direct drive, diesel-powered 2-inch (5-cm) centrifugal, cast iron, self-priming pump (Yanmar TS50/YKS-2D) is currently installed. The intake is mounted 0.9 m above MTL. In emergencies an electric-powered, 0.75-kw centrifugal self-priming pump powered by a portable generator is available.

The seawater pump is usually run for at least 12 hours each day (0700–1900). The current pumping system provides at least 10.8 m^3 of seawater/hour and the total volume of water that can be held in the tanks and raceways is 50 m^3. Thus during the average pumping day the seawater in the system is exchanged a minimum of 2.5 times. In times of heavy rainfall the pump can be left running all night.

Reticulation system The main reticulation system is through 80-mm PVC pressure pipes mounted 2.3 m above the ground on upright coconut logs. The pipes are covered in sisalation paper to reduce heating and to prevent UV degradation of the pipes. Each pair of tanks and raceways are fed by 50-mm tees off the main lines with reducer fitting and 1-inch (2.5-cm) ball valve for each tank or raceway. The feeds for each tank pair are interchangeable by means of 50 mm barrel unions.

Tanks Three types of tanks are currently in use: ferrocement, vinyl and fibreglass. All are circular with a central drain and standpipe, and arranged in groups of four with a common drain sump. Thus any tank can be back-filled from its opposite tank by removing the standpipes and connecting the drain pipe using a compression coupling. The tanks are raised approximately 30 cm above ground level on square sand platforms formed with coconut logs. Raising the tanks allows easy access to the drain. The specifications of the different tanks are given in Table 1.

TABLE 1. Specifications of tanks in use at the CAC.

Tank type	Number	Diameter (m)	Depth (m)	Volume (m^3)	Surface area (m^2)
Ferrocement	5	3.00	0.65	4.59	7.06
Vinyl	4	2.45	0.50	2.35	4.71
Fibreglass	4	1.80	0.40	1.01	2.54

The fibreglass tanks are currently used for broodstock holding and spawning because of their small size and robustness. The vinyl tanks are suitable for larval culture because of the ease with which they can be drained and cleaned. The ferrocement tanks have proved to be good larval culture and settlement tanks because of their large surface area and textured surface.

Raceways Eight raceways have already been constructed, consisting of blue woven polyethylene 'Canvacon' fabric fitted between four sections of coconut log on a sandy base. The fabric is available in 1.83-m wide rolls, giving a raceway with a depth of approximately 0.3 m and a width of 1 m. The raceways have been constructed 5 m long. At the drain end a 50-mm flange fitting has been glued on to take a standpipe. Alternatively an elbow fitting can be placed on the outlet to give a swinging arm arrangement.

Some initial doubt existed about the suitability of the raceways for juvenile culture because of their shallowness and lack of texture if no other substrate was provided, but it has since been found that juveniles will attach firmly enough to withstand draining and hosing, and that temperature increases in the raceways do not exceed 1°C above that of ambient seawater temperature, provided that seawater supply during the day is maintained. The raceways can be covered with shadecloth during enforced water stoppages and tarpaulins in heavy rain.

Drainage system All the drains have been constructed from 15 mm galvanised birdwire and cement for ease of construction and cheapness. Halved 40 cm lengths of concrete drainage pipe have been used on the drainage sumps for each group of four circular tanks to avoid overflow when draining

and provide a convenient area for sieving. All drains are open to allow easy maintenance and inspection.

Facilities Planned

Pumping A back-flushing system will shortly be installed to enable freshwater to be pumped from land into the intake line. This will facilitate cleaning of the intake screen and prevent fouling of the intake line.

A 4-inch (10-cm) direct-drive diesel pump (Yanmar TF80/SB4) will be installed in the pump house. In the short term this will provide backup for the existing pump and increased pumping capacity when high flow rate is required. It will also enable a considerable expansion of the existing tank raceway system.

Expansion of tank/raceway system The existing reticulation system has been constructed with a number of blind tees to enable expansion as required. The immediate priority is the construction of three more ferrocement tanks, for which the pads have already been constructed, and the fabrication of eight more raceways.

Development of hatchery The concrete pad and drainage system for the hatchery to be developed under the office/laboratory building has already been constructed and the seawater distribution line been extended towards the building. Two 1.8 m^3 fibreglass culture tanks are already available for use.

Culture Methods Used

Broodstock

Thirty-five broodstock were collected from Santa Ysabel Island and Marovo lagoon in July and August 1987 and placed 4 m offshore of the site (Govan, This Monograph).

The sizes of the broodstock were as follows:

	Origin	
Size-classes (cm)	Marovo	Ysabel
70.0–79.5	1	1
60.0–69.5	9	5
50.0–59.5	10	3
40.0–49.5	3	3

At any one time at least 15 broodstock are held in the fibreglass tanks, in preparation for spawning.

Spawning

Biopsies carried out in October on all the broodstock were not particularly encouraging. Whereas there was no difficulty in most cases of sampling the gonad, only two of the samples taken showed evidence of free-floating round eggs of approximately 100 μm diameter. However spontaneous spawnings of broodstock occurred in both our tanks and on the reef in November 1987, and January, February and March 1988.

Wherever possible eggs are collected in plastic bags held over the exhalant siphons of the spawning clams and the eggs transferred to clean tanks filled with fresh seawater, as eggs left in spawning tanks or siphoned into adjacent tanks have had poor survival. Eggs from clams from the two different localities were kept separate. Initially only certain tanks were filled with 20 μm filtered seawater due to lack of filters, but since March 1988 the use of cartridge filters has allowed all eggs to be stocked in seawater filtered to 25 μm.

Larval Rearing

Larval rearing has been carried out in the outdoor tanks to date. The method employed (workload permitting) may be described as semiintensive, being more intensive than that described by Heslinga et al. (1984) but less intensive than the conventional bivalve rearing method tried for *T. gigas* by Crawford et al. (1986). Permanent water flow has been restored to the tanks after 10–14 days depending on the rate of settlement of the larvae. Attempts were made to use continuous flow during the planktonic stage by the use of 53 μm sieve cloth placed over the standpipe. Due to clogging this was found unsatisfactory, and a method of keeping the screen clear is being developed. In March 1988, the system was intensified further by better filtration of the water used to fill the tanks, the use of aerators to improve water circulation in the tanks and flocculate off debris, and frequent sievings of the tanks to improve water quality.

To date zooxanthellae have been isolated by scraping off cuttings of clam mantle taken from the broodstock and passing the resulting liquid through a 25 μm sieve. These have been added to the settlement tanks containing 7–10-day-old larvae to give concentrations of approximately 26 cells/ml.

Attempts have also been made to obtain cultures of local phytoplankton by filling outdoor 1000-l fibreglass tanks with 10-μm filtered seawater and fertilising with a commercially available hydroponics fertiliser. The predominant algal species have not been identified but include some small motile green algae less than 2 μm diameter. These are added to the settlement tanks to give concentrations of up to 7000 cells/ml.

Harvest and Culture of Juveniles

Three-month-old juveniles are harvested by scraping the sides and bottom of the tanks with a rubber scraper and siphoning off the clams and algal mat into buckets. The resultant mix is cut through a 3-mm sieve with water jets to break up the algal mat and separate out the clams, juveniles retained on the sieve being picked off by hand. Floating algal

fragments are decanted off through a 500-μm sieve. This is repeated several times until an almost pure sediment of clams is left in the bottom of the buckets. This method is time-consuming, but effective. Equipment is currently being developed to automate the process.

After harvest, juvenile clams are weighed, subsampled, counted and measured and stocked into raceways.

Results

There have been three major and two minor spawnings since the first spawning activity (late October 1987) was seen in broodstock held in tanks. Although some spawning activity had been noted in October 1987, the first major spawnings occurred on 5 and 6 November 1987 from which approximately 300 million trochophores were obtained.

Minor spawnings occurred on 15 November 1987 and 15, 16 and 18 January 1988. Further major spawnings occurred on 7 February 1988 from which approximately 113 million trochophores were obtained and 8 March 1988, which produced nearly 200 million trochophores. Two clams injected with serotonin on 3 November 1987 released sperm, but all egg releases observed so far have been spontaneous. All but one of the clams that produced eggs were over 60 cm shell length, but the majority of eggs were obtained from clams larger than 69 cm. At present it is not clear what has been the stimulus for spawning.

In February 1988 the juveniles from the first spawning of 5–6 November were harvested from the ferrocement settlement tanks, yielding a total of 75 000 three-month-old *T. gigas*. The yield per tank varied considerably, two tanks giving 45 000 and 26 000 juveniles respectively, with the other three tanks yielding less than 2000 juveniles each.

The juveniles have been stocked into three raceways where they are currently strongly attached and growing. Mortalities and growth rates for these have yet to be calculated.

One settlement tank currently contains very large numbers of 2.5-month-old juveniles (probably in excess of 100 000), and each of the other four tanks contains large numbers of 1.5-month-old juveniles.

Comparison of Different Hatchery and Nursery Culture Methods for the Giant Clam *Tridacna gigas*

Richard D. Braley*, Warwick J. Nash, John S. Lucas* and Christine M. Crawford****

Abstract

Various mass-culture techniques for giant clam larvae and juveniles have been tested to try to improve survival. *Tridacna gigas* larvae were mass-cultured using Intensive (I) and Semi-Extensive (E) methods. These methods included a Selection (S) process, in which the hatchery tanks were stocked with swimming veligers rather than fertilised eggs (compared with Non-Selected (NS) larvae). Selection resulted in 60% survival of D-stage veligers from eggs. In terms of the survival of eggs to 6+ month-old juveniles, although the best percentage IS was superior to ES and ENS, survival was only 2.24%. Experiments on the effects of different substrates on settlement and survival of juvenile clams showed that the survival was highest with a combination of IS and carborundum (dark, rough). Clams were also larger on this substrate than on others. Juvenile clams up to 6–8 months of age were larger in all NS than S culture systems, but this may be related to the lower density of juveniles in NS. The shaded side of tanks was no different from the sunny side in terms of survival and size of 6-month-old juveniles. A new flow-through technique resulted in large production of 2-month-old juveniles from ES culture but low to moderate production from ENS culture.

BEFORE commercial-scale giant clam culture can be realised great improvements must be made in the hatchery production of 6–9-month-old seed clams which can be transferred to the ocean-nursery phase of culture. Although improvements have been realised from laboratory culture (La Barbera 1975; Jameson 1976; Beckvar 1981; Gwyther and Munro 1981) to mass culture techniques (Heslinga et al. 1984; Crawford et al. 1986) the survival from eggs to seed clams has been in the range of 0.04–0.36%. The highest mortality occurs in the preveliger and postsettlement stages. Some laboratory-scale research has been directed at determining conditions to improve larval and juvenile survival (Fitt and Trench 1981; Fitt et al. 1984; Braley 1986). Fitt et al. (1984) found that trochophore mortality remained at least 80% despite great care, and that survival and growth of veligers was best at 0.2–10 larvae/ml and growth superior when fed the microalgae *Isochrysis galbana* (Tahitian strain) or vitamins and yeast extract. Braley (1986) found limited use of antibiotics greatly improved the survival of the developing embryo and trochophore to D-veliger stages. Also, *I. galbana* (Tahitian) and *Pavlova salina*, an alga not previously reported for use in larviculture, were found to be equally good foods for growth and survival, and feeding was best commenced on the second day of the veliger stage due to poor survival associated with earlier feeding.

This paper reports on large experimental-size *T. gigas* culture at Orpheus Island Research Station between 1985 and 1988, comparing survival and size of juveniles from (1) intensive culture (I) vs semi-

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extensive culture (E) and a variety of different treatments; (2) non-selected (NS) vs selected (S) larve; (3) a flow-through hatchery system; and (4) substrate type and shaded/sunny sides of nursery tanks.

Materials and Methods

Intensive Culture

After spawning and collection of gametes, fertilised eggs were left to settle for 2 hours in 60-l plastic bins. The concentrated eggs were siphoned through a 200-μm sieve into clean plastic bins, topped with 1-μm filtered seawater (FSW), an estimate made of total eggs and fertilisation rate, and eggs were then set into tanks for the selection process. Selection involved the use of antibiotics (5–7 ppm chloramphenicol or streptomycin) for a period of 40–48 hours after fertilisation. Larvae were swimming D-stage veligers at this stage and only swimmers in the upper portion of the water column were siphoned onto an 80 μm screen; dead or dying larvae or eggs on the bottom of the selection tank were discarded onto hot sand. Antibiotics were no longer used and larvae were transferred into hatchery-rearing tanks after survival rates were estimated.

Veligers were stocked in fibreglass tanks ranging from 200 to 2000 l at densities ranging from 2 to 10/ml though most batches subsequent to early 1986 were stocked at about 5/ml. There was a daily 1-μm FSW change of 40–100%. Culturing took place in both temperature-controlled and ambient temperature rooms and an intitial trial in 1988 used a flow-through system (described later). Tanks were lightly aerated. The unicellular algal species *Isochrysis galbana* (Tahitian) and *Pavlova salina* were fed at concentrations of 10–100 cells/μl. Survival rates were estimated at intervals throughout the larval period and at settlement. Settled larvae were then stocked in large outdoor tanks (2000–10 000 l) in various treatments at 5/cm^2 bottom area and managed similar to tanks from other larval culture methods for up to 6–8 months before transfer to the ocean-nursery phase.

Semi-Extensive Culture

Extensive Non-Selected (ENS) reared larvae were stocked in large outdoor tanks at 2 eggs/ml in 1-μm FSW with a 50% shadecloth cover, aerated and fed mass-cultured *I. galbana* (Tahitian) or *P. salina* at about 10 cells/μl. Algae were added when algal counts decreased below this optimum level. Seawater was flushed (50% replacement) if conditions required this. Selected larvae (S) were stocked in large outdoor tanks (2000–10 000 l) at 1/ml.

Substrate and Shade in Nursery Tanks

The main experiment from the December 1986 batch used seven 3000-l round fibreglass tanks with alternately arranged quarter sections of two substrates (carborundum plates and fibreglass tank bottom). Here, survival, substrate effect and shaded (north side of tank) vs sunny (south side of tank) were tested. In the December 1985 batch two 4000-l round tanks and two 2000-l raceway tanks were used as replicates to test substrate preference and survival. Here, four substrates were tested, two per tank, using alternately arranged quarter sections (dark rough, dark smooth, light rough, light smooth).

Flow-Through

An early 1988 trial was set up with the use of a flow-through system which was similar to a design used in a recirculating larval system for barramundi (*Lates calcarifer*) (Russell et al. 1987). In our Flow-Through system a 100-μm mesh screen was used with a flotation container through which the standpipe was placed, and was used in four 10 000-l tanks (2 ENS, 2 ES). A circular airstone placed below the screen gently swept away larvae if held against the screen. In this system a single pulse feeding of outdoor mass-cultured microalgae was added to the tanks daily at the specified rate described in extensive culture. Water flow in 10 000-l tanks was adjusted for one change in 36 hours. After settlement, a 25-μm FSW flow was increased to one daily turnover and flow-through screens removed.

Results

A summary of the main batches of *T. gigas* spawned between February 1985 and February 1988 is given in Table 1. Some records are scarce for early batches but a general trend toward an increase in survival from eggs to juveniles over the 3-year period is evident in the IS data. The IS method shows a large increase in survival over the INS method, and even the ENS method shows better survival in the past 2 years than the initial INS method. The IS method shows at least a 10-fold increase in survival over ENS for cohorts from a spawning. This early survival from eggs is shown graphically in Fig. 1. The most striking feature in both Table 1 and Fig. 1 is the large losses between settlement and 2 months of age regardless of culture method. At 2 months of age ES flow-through method (January 1988 spawning) showed a similar survival to the IS method (December 1986 spawning) while the ENS method from both years was similar (Fig. 1).

The experiment (December 1986 spawning) on culture methods was tested with a one-way ANOVA

TABLE 1. Summary of survival of *T. gigas* main larval batches from spawned egg to 6–8 months of age. Culture methods indicated as IS (intensive selected), INS (intensive non-selected), ES (extensive selected), ENS (extensive non-selected).

Spawning date (site)	Treatment	Fertilisation rate — %	% survival to D-veliger	% survival to Settlement	% survival to 2 months	% survival to 6 months
2.85 (OIRS)	INS	–	–	–	–	0.04*
10.85 (OIRS)	INS	–	69.0	–	–	0.09
1.86 (OIRS)	INS	–	0.65	0.17	–	0.05
1.86 (Seafarm)	IS	97.10	63.10	10.87	–	0.18**
12.86 (OIRS)	IS	80.0	75.0	51.60	2.12	2.24
	ES	80.0	–	–	0.26	0.07
	ENS	80.0	–	–	0.19	0.15
12.86 (OIRS)	IS	97.0	90.0	81.20	2.44	1.36
	ES	97.0	–	–	0.30	0.14
1.88 (OIRS)	ES	89.6	55.8	–	2.54	–
	ENS	89.6	–	–	0.18	–
2.88 (OIRS)	IS	85.3	17.4	3.53	–	–

* Survival from pediveligers.
** Low salinity, no water flow after Cyclone Winifred, 1 February 1986.

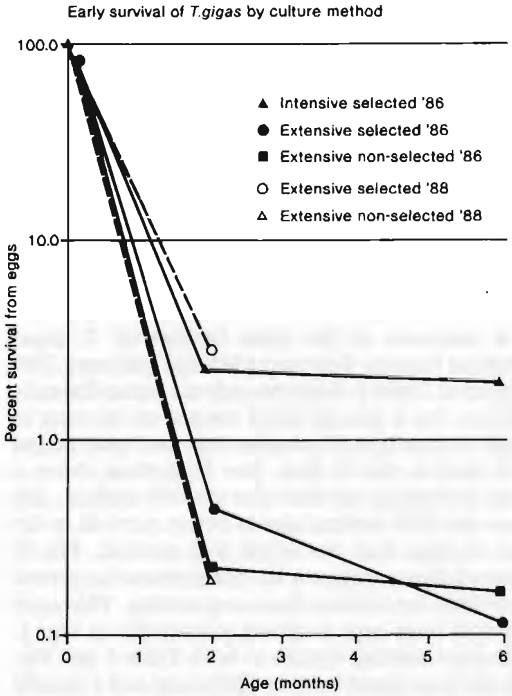

Fig. 1. Early survival of *Tridacna gigas* by three culture methods. Three methods shown to 6 months of age were spawned December 1986; two methods shown at 2 months only were spawned January 1988. *Note*: The slope of the mortality curve in the first 2 months is probably steeper than indicated but we have no hard data for this period to indicate otherwise.

for percent survival from eggs to 6 months of age, using square root transformed percentages. Transformation of data was necessary because percentages were not significant. Superiority of the IS over ES or ENS methods was significant at $p = 0.05$. A power analysis utilising the non-centrality parameter (Winer 1971) on untransformed data indicated that there was less than a 50:50 chance of detecting a significant difference between treatments of the magnitude indicated intitially with 2 tanks per treatment; if we could have afforded 5–7 tanks per treatment (15 total) we would have 82–96% chance of detecting a significant difference between treatments. The constraint of available tanks makes a somewhat obvious result difficult to show by analysis of variance. The size of juveniles in the experiment at 6 months was significantly smaller (*t*-test, $P < 0.05$) in IS than ENS methods.

The flow-through system (January 1988 spawning) was tested by nested one-way ANOVA for production/survival. ES method was significantly better than the ENS method ($P < 0.05$). The production ± SD from the ES method was 455 800 ± 77 000 clams/10 000-l tank while the ENS method was 37 700 ± 31 700 clams/tank. The size of 2-month-old juveniles was significantly smaller (*t*-test, $P < 0.01$) in the ES than the ENS method.

Density of clams in the January 1988 spawning at 2 months of age was significantly greater in ES than ENS method (*t*-test, $P < 0.01$), but was not significant (*t*-test) for the December 1986 spawning at 6 months of age.

Production of juveniles was significant (two-way ANOVA and SNK test, $P < 0.01$) for a combination of rough, dark (carborundum) substrate. Colour/

texture substrates gave different results in the two raceways and two round tanks, presumably due to the low number of replicate tanks. In the two raceways, light, smooth had the greatest production/survival of clams (two-way ANOVA, $P < 0.01$). In the two round tanks a rough surface alone was responsible for the greatest production/survival of clams (two-way ANOVA, $P < 0.01$).

The shaded (northern) side vs sunny (southern) side of tanks (December 1986 spawning) showed no significant differences (*t*-test) for either production/survival or size.

Discussion

Braley's (1986) successful use of antibiotics in the early larval period led to the mass selection technique described here. Our results show that a mean of 60% survival from eggs to D-stage veliger of *T. gigas* is attained with our selection method. This is far higher than previous results from either laboratory-scale studies (Fitt et al. 1984) or mass culture (Heslinga et al. 1984; Crawford et al. 1986).

Our data show the importance of the selection method to survival/production of 2-month-old clams when used in the flow-through system described in this paper. The density is about 5.5 times our previous best density. Our data from the December 1986 spawning also show the significance of selection. In the ENS method a portion of the eggs added will not be fertilised, and will die after several divisions, or later in the embryonic development. This will contribute to bacterial blooms and make conditions unfavourable for both the swimming larval stage as well as the settlement/metamorphosis period. In selection, only healthy swimming veligers are added to a clean tank of 1-μm FSW. This simple step can help increase survival both at the preveliger and postsettlement stage.

The size difference between selected and non-selected treatments may be a function of density of juveniles. Growth may be poorer in the high-density situation because of a presumed direct relationship between dissolved nutrient availability and density. Results of a recent study at the MMDC in Palau (MMDC Bulletin, March 1988) suggest the nutrient levels in clam tanks may be suboptimal. They found that clams treated with fertilised seawater grew 15% faster than controls without fertilised seawater. In our selected treatments the use of antibiotics in the embryonic stages may also be suggested as a factor contributing to smaller size of seed. However, growth rates and size of 16- and 27-month-old *T. gigas* subjected to selection of embryos-veligers are growing normally in the ocean-nursery phase (Braley, unpublished data).

Size and densities of juveniles were found to be much higher on textured than smooth surfaces by Crawford et al. (1986), and this was confirmed by our data where carborundum was the textured surface tested. Furthermore, a combination of carborundum and IS method of culture was found to have the most influence on production/survival. A behavioural factor may be involved here since settled/metamorphosed clams still move about very actively with their foot. They may use up energy searching for a more suitable substrate rather than put this energy into somatic growth. The slightly textured surface of the plastic liners used in the flow-through system may be the most economical way to provide this preferred surface for setting larvae.

Compared with our semiextensive system of culture, Heslinga et al. (1984) do not feed larvae cultured algae, although a natural algal bloom is allowed to develop in the tank over the period of the larval cycle. The mean survival of 6-month-old juveniles from stocked eggs was about 0.1% (Heslinga et al. 1984) but the human time and effort put into the culturing was less than in our semiextensive system. The economics of these culture systems need further analysis.

There still remain serious problems in tanks with the growth of benthic filamentous algae. These algal species may overgrow the clam juveniles, thus reducing light and the exchange of fresh seawater available to the clams. Research is needed to understand the factors contributing to why certain species/varieties of benthic algae become established rather than other species/varieties. Some benthic algae appear to be less detrimental to juvenile clam survival because of the ease of removal by siphoning. Heslinga et al. (1984) used hatchery-reared juvenile *Trochus niloticus* to graze benthic algae on and around juvenile clams, but in our experience juvenile trochus were not efficient at grazing the algae. When the juvenile clams were 8 months old small adult trochus could then be used efficiently to graze algae, but the amount of faeces produced by the trochus made their value questionable. The use of herbivorous fish suggested by Heslinga (pers. comm. 1987) may have value after juvenile clams are large enough not to be swallowed by the fish with their algal dinner. Our use of two layers of 50% shadecloth in the first 3 months (one directly over the tank, one on a walk-under canopy) reduces light levels to about 400 $\mu E/m^2/sec$ at midday on a sunny day. At this level of light intensity the photosynthetic rate is only slightly reduced from that at 1000 $\mu E/m^2/sec$ for small juvenile *T. gigas* which have very thin, translucent mantle tissue (Fisher et al. 1985). The reduced light intensity thus helps limit the initial growth of benthic filamentous algae without proportional detriment to juvenile clams. After several months a weekly schedule of wafting the loose benthic algae off the bottom and siphoning from the tank was employed.

Further improvements are required in this period of culture.

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Ocean-Nursery Phase for Giant Clams in the Central Visayas, Philippines

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Abstract

From late 1985 to early 1988 approximately 5000 juvenile clams have been transplanted to seven areas in the Central Visayas, Philippines. Of all the chosen sites, clams placed at Pamilacan had the highest survival. The cage type used in this area afforded only partial protection (open at top) and used ipil-ipil for pegs and net for enclosure. Pamilacan was recommended as a candidate for a large-scale ocean nursery in the Central Visayas region.

THE transfer of laboratory-reared clams to ocean nurseries is one of the ultimate goals of the ACIAR-funded Giant Clam Project. In late 1985, the Marine Laboratory started a small-scale ocean nursery at the reserve area of Apo Island using *Tridacna derasa* from Palau, Western Caroline Islands. Several small-scale ocean nurseries were then established in various islands in the Central Visayas during the succeeding years.

This paper gives an overview of all the ocean nursery sites established within seven areas in Central Visayas since late 1985.

Objectives

The objectives of the grow-out phase of the project are:

1. To determine areas in Central Visayas best suited for the establishment of an ocean nursery;
2. To develop a cage offering maximum protection, and made of inexpensive, durable and locally available materials;
3. To determine the ages at which clams can be transferred to ocean nurseries; and
4. To determine the age at which clams can be placed in the field without any mesh protection.

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Materials and Methods

Study Areas

Joint cooperative efforts with other projects have led to the establishment of ocean-nursery sites in various islands in Central Visayas. Under the auspices of MCDP (Marine Conservation Development Project), local communities of Apo Island (Negros Oriental), Balicasag and Pamilacan islands (Bohol) sanctioned the establishment of marine reserves within these islands. Utilising the community involvement of CVRP (Central Visayas Regional Project), field data on clam growth were obtained with the cooperation of local fishermen interested in clam farming.

Priority was given to islands with marine reserves and established local community relationships to minimise the possibility of poaching and to ensure the participation of the locals in guarding and monitoring the clams, especially after rough weather conditions. Clams were then given either to the community, an association of the community, or interested local fishermen.

The following sites were chosen for the small-scale ocean nurseries:

Apo Island Reef is a diverse coral reef community. The southeast portion of the island is a marine reserve. Here, cages were placed on sandy patches within the reef.

Balicasag and Pamilacan islands are located southwest of mainland Bohol. The marine reserve

of Balicasag Island is at the southeast portion of the island and cages were placed on sandy-coral rubble substratum among dead standing corals. The ocean nursery of Pamilacan Island was established inside the reef, which is a mixed seagrass community.

Solang-on, located southwest of Siquijor Island, is one of the study sites of CVRP. Clams were placed in a mixed seagrass community similar to Pamilacan Island.

Bindoy, Negros Oriental is another site of CVRP. Several local fishermen interested in clam farming were initially given clams in exchange for field data on clam growth. The areas where cages were placed depended on each fisherman and these areas varied from each other in terms of water turbidity and presence of coral reef.

Danajon Bank is a shallow sandy flat located between the islands of Leyte and Bohol. The area is characterised by strong currents, a requirement in *Eucheuma* farming. The small-scale ocean nursery is a joint effort of the Marine Laboratory and Marine Colloids Philippines Incorporated (MCPI), one of the corporations that farms *Eucheuma* in the area.

Carbin Reef is a coral cay located off the northern coast of Negros Occidental, where a marine reserve was established 2 years ago. Cages were placed on sandy areas within the reef.

Bantayan Beach is located right in front of the Marine Laboratory. The ocean nursery of the Marine Laboratory was placed in a mixed seagrass community at the edge of a coral reef. The cages of a fisherman cooperator, Dioscoro Inocencio, were also placed within a mixed seagrass community in Bantayan.

Cage Design

Cage designs were patterned according to interviews with local fishermen regarding cheap and available materials and also observations on the materials utilised for fishing (e.g. fish trap, gill nets).

Age Determination

To determine age at which clams can survive in ocean nurseries, clams of various ages were placed in chosen sites. Nine- to eleven-month-old *T. squamosa* juveniles (10–20 mm) were placed in Solang-on, Bantayan and Pamilacan islands. In these three areas, ocean nurseries were placed in mixed seagrass beds and clams were placed within the same cage design.

For *H. hippopus*, an attempt was made to transfer < 1-year-old juveniles to chosen ocean nurseries. Older clams (12–14 months old) were also transplanted to chosen sites: Apo, Pamilacan and Bantayan.

To determine the age at which clams could survive without any form of mesh protection, 18–19-month-old *H. hippopus* juveniles were placed on coral rubble-sandy substratum with piles of dead coral as enclosures at the islands of Apo and Balicasag and Danajon Bank.

Results and Discussion

Cage Design

Taking into consideration the ultimate transfer of clam farming to local fishermen, three types of cages were designed for the various ocean nurseries. Cheap, locally available materials were used (e.g. nylon nets as cover and bamboo, ipil-ipil or iron bar as pegs or frames). Dead corals for clams to attach to were placed inside.

The original cage design used iron bars for the frame and gill net for cover. These cages were placed in Apo Island and Carbin Reef. Although iron bars may be very durable, they are expensive for fishermen. The other two designs using bamboo and ipil-ipil are now used in the later ocean-nursery sites.

The second design is similar to the original but instead of iron bars, bamboo slats were used for the frame. Enclosures of nylon nets can be made by the fishermen themselves or bought in local stores, which provide a range of mesh sizes. A disadvantage in making the net covering is that smaller mesh sizes are difficult to make. Fishermen cooperators in Bindoy and Bantayan streamlined the dimensions along this cage design.

The third type used bamboo primarily designed like the popular Filipino fish trap. A drawback in this cage type is the time-consuming preparation of the bamboo (e.g. bamboo has to be 'skinned' or the outer, shiny layer removed and split into very thin slats). Fishermen prefer using gill nets since aside from their availability, old and torn fishing nets can be reused.

The fourth cage design is a simple fence-like enclosure of nylon net held in place by ipil-ipil or bamboo posts. A flooring of finer nylon mesh may be placed, as in the ocean nursery in Bantayan Beach. In Balicasag and Pamilacan islands, there was no flooring within the enclosures.

Survival

Clam survival at the various ocean-nursery sites from late 1985 to early 1988 is shown in Table 1. Comparing percent survival of clams in the oldest ocean nurseries (Apo Island, 24 months; Balicasag, 21 months; Pamilacan, 17 months; and Bantayan, 15 months), highest value was obtained in Pamilacan Island (74%). Clam survival at other sites after 3–4 months was highest at Danajon Bank (76%, *H. hippopus*) followed by Pamilacan (73%, *T. squamosa*).

TABLE 1. Mean growth and survival of juvenile clams at various sites in Central Visayas from late 1985 to early 1988. Mean growth before death given in parentheses.

	Survival (%)	Mean growth of remaining clams (mm/month)
H. hippopus		
Apo Island	0	(5.33)
Carbin	0 (all stolen)	(1.32)
Balicasag	16 (after 21 months)	3.82
Pamilacan	74 (after 17 months)	3.65
Danajon	76	1.3
Bindoy	26 (some stolen)	2.96
Bantayan	50 (after 15 months)	2.64
T. maxima		
Apo Island	0	(3.2)
Bindoy	0	—
T. derasa		
Apo Island	49 (after 24 months)	5.3
Carbin	0	(5.6)
T. gigas		
Apo Island	30	6.8
T. squamosa		
Siquijor	9	4.57
Bantayan	19	2.85

It was noted that *T. derasa* placed in Carbin also had high percent survival (95%) after 12 months before they were stolen. The low percent survival of clams in Bindoy (24%) is partially due to poaching.

Although both Pamilacan and Bantayan clams were placed in a mixed seagrass bed, percent survival is lower at Bantayan which is exposed to the northeast monsoon trade wind. According to the locals at Pamilacan, the ocean-nursery site is exposed during southwest monsoon but no rough weather conditions occurred during October 1986–March 1988. It has been observed by our fisherman cooperator of Bantayan that most mortalities of his clams occurred after rough water conditions.

The ocean nurseries at Apo and Balicasag islands are located within and adjacent to the coral reef, respectively. At Apo Island, dead shells collected were mostly crushed or chipped off at the edges and some had holes through the shells. Gastropods, mostly *Murex*, have been observed and removed from ocean-nursery cages.

Comparing these values obtained with *H. hippopus* at Silaqui and Tomasa, Pangasinan (96.8–97.6 and 66.7%, respectively) (UPMSI 1987), survival at Silaqui is higher than values obtained within our ocean-nursery sites in the Visayas.

Growth

Growth of *H. hippopus* in the various ocean-nursery sites was variable (Table 1). However, some generalisations can be made. Highest values were obtained from *H. hippopus* placed in Apo Island, 1 month before they all died. Shell increment of the same species in Pamilacan and Balicasag was also high (3.6 and 3.8 mm/month, respectively).

Tridacna gigas from James Cook University had a mean growth rate of 6.8 mm/month which is comparable to mean growth rates attained from floating racks in Pioneer Bay, Orpheus Island (Crawford et al. 1988).

The mean growth rates attained from ocean nurseries in Central Visayas is within the projected growth/year reported by Beckvar (1981).

Field data of *H. hippopus* juveniles in Central Visayas reveal a high rate of shell increment and survival in Pamilacan Island. As mentioned, the ocean nursery is partially protected from the monsoon trade winds, which have been known to destroy cages, overturn clams, and chip off shells.

Although high survival was obtained at Danajon, growth was slow. According to Beckvar (1981), faster increase in shell length is expected in areas with slow currents. In areas with strong currents, clam growth is manifested in the increase of shell thickness rather than length.

If a large-scale ocean nursery is established in Central Visayas, Pamilacan Island should be considered a candidate despite the 6-hour pumpboat ride from Dumaguete City. However, if we want to encourage sustenance fishermen to farm clams, studies should also be made on growth and survival of clams in areas exposed to wave action, a characteristic of coastlines in Central Visayas.

Age and Size Effects

Jameson (1976) recommended a 30–40 mm size range of clams for field introduction. However, for large-scale farming purposes, the transfer of younger and smaller clams would be economical. In Palau, 5–7-month-old *T. derasa* juveniles (20–30 mm) are introduced to the ocean nursery (Solis, pers. comm. 1988).

Table 2 shows the growth and survival of *T. squamosa* and *H. hippopus* juveniles of various ages in the field. Nine- to eleven-month-old *T. squamosa* (10–20 mm) were transplanted to the ocean nurseries of Bantayan, Siquijor and Pamilacan with partially protected cages (cages without covers). Juvenile *T. squamosa* in Bantayan had very poor survival although clams were allowed to attach to dead coral before being placed in the ocean nursery. Subsequent rough water conditions occurring 1–2 weeks after the transfer dislodged the clams from the dead corals. Of the 710 *T. squamosa* juveniles placed in Siquijor, only 61 were found after 4 months (9% survival). We presumed juveniles to be dead although it is very possible that some may be just within the vicinity. The juveniles placed in

TABLE 2. Summary of the growth and survival of *T. squamosa* and *H. hippopus* juveniles in chosen ocean-nursery sites. Mean growth before death shown in parentheses.

Locality	Age upon placement (month)	Size Range (mm)	Mean growth (mm/month)	Survival (%)
T. squamosa				
Solang-on, Siquijor	9	10–20	4.56	9
Bantayan, Dumaguete	10	15–20	–	0
		10–15	2.8	27
		10–17	2.92	11
		10–14	2.8	21
H. hippopus				
Apo Island, Negros Oriental	5	15–29	(5.56)	0
	10	33–61	7.54	0
	12	24–42	–	0
	13	30–40	(2.9)	0
Carbin Reef, Negros Occidental	14	30–50	(1.32)	0
Pamilacan Island, Bohol	14	60–80	3.6	70
Bantayan, Dumaguete	11	50–65 (after > 1 year in ocean nursery)	2.6	50

Pamilacan have the highest growth and survival (12 mm/month and 73%, respectively). Field trials done in Palau on 10–20 mm *T. squamosa* juveniles placed in open Nestier trays suffered total mortality (Heslinga et al. 1984).

The 5- and 10-month-old juveniles placed at Apo Island exhibited high monthly length increments (5.56 and 7.54 mm respectively) before they all died. Eleven-month-old *H. hippopus* in Bantayan exhibited lesser growth but 50% were still alive after more than a year in the field (Table 2).

For *H. hippopus* over 1 year old, only clams in Pamilacan survived to early 1988. The surviving clams in both Pamilacan and Bantayan were larger when transplanted.

As clam growth varies within a cohort, a question arises whether to base on age or size of clams the time of transfer from land-based nursery to ocean nursery. Our results indicate that size range would be a better basis for higher chances of survival of juveniles in ocean nurseries.

Table 3 shows the growth and survival of clams placed in the field without any form of mesh protection. All the clams placed in Apo Island were lost after 2 months. Clams placed at Danajon Bank had a high survival (76.5%) but slow growth (1.29 mm/month). In Balicasag, the clams that were transferred from cages to the outside suffered 97% mortality, but the remaining clams had high shell growth increments (5.1 mm/month).

According to the local caretaker at Apo Island, the total mortality of the unprotected clams at Apo may have been caused by an eagle ray which was observed within the vicinity at dusk. However, we

TABLE 3. Growth and survival of *H. hippopus* in unprotected ocean nurseries.

Locality	Age upon placement (months)	Size Range (mm)	Months in the field	Mean growth (mm/month)	Survival (%)
Apo Island, Negros Oriental	18	81–89	2	–	0
Danajon Bank, Bohol	18	62–83	5	1.29	76.5
Balicasag Island, Bohol	19	37–62	6	5.1	2.99

were not able to see the ray when we were there. The eagle ray (*Aetobalis* sp.) was also identified by Heslinga and his colleagues (1984) as the possible predator of some clams released unprotected in the reef. In some instances, shells were found in the mouth of crevices under corals (suspected to be crab holes), far from where these clams were released.

Attempts to release unprotected clams were also made at Orpheus Island, Australia (JCU 1987). Only one crushed shell was recovered and only one survived for only a few weeks.

The strong current in Danajon may account for the low increase in shell length exhibited by clams, since strong current may induce thick shell growth (Beckvar 1981).

In the application of large-scale ocean nurseries, an area affording optimum growth and survival without the additional expense of cages would be very desirable.

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Spawning and Larval Rearing of Giant Clams in Pangasinan, Philippines

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Abstract

Spawning induction of *Tridacna squamosa* and *T. maxima* was done by intragonadal injections of serotonin and gonad slurry. *Tridacna squamosa* gonad has successfully induced spawning also in *T. maxima*. Spontaneous spawning was observed for *T. maxima, T. squamosa* and a mixed batch of *T. maxima* and *H. hippopus*. Larvae from the veliger stage were fed *Isochrysis galbana* and zooxanthellae isolated from available adult clams. Growth curves of the various batches that survived to juveniles are presented. Early harvest and deployment to the ocean nursery is recommended to increase survival and promote better growth rates.

GIANT CLAMS are exploited for their meat and shells to various degrees in many areas of the Indo-Pacific, but always with greater preference for the larger species, so that disappearance of these species has occurred in certain areas of their range (Hester and Jones 1974; Bryan and McConnell 1976; Yamaguchi 1978; Hirschberger 1980; McKoy 1980; Brown and Muskanofola 1985). In the Philippines, giant clam meat is both for local consumption and export, while the valves form a significant part of the shell trade (Juinio et al. 1987). The demand for giant clams has resulted in the overexploitation of all species and widespread local extinction of *Tridacna derasa, T. gigas, Hippopus hippopus* and *H. porcellanus* (Alcala 1986; Juinio et al. 1986; Villanoy et al. 1988). The development of the technology for giant clam mariculture and seafarming in recent years has opened up avenues not only for an abundant and steady supply of clam products, but also a means of providing alternative sources of food and income for coastal inhabitants as well as a source of seed clams for restocking depleted reef areas. In our case, many of the juveniles we have reared have also been used for growth studies.

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In February 1986, the Marine Science Institute giant clam hatchery in Bolinao, Pangasinan, was completed and mariculture trials were started soon after (Trinidad-Roa and Alialy 1988). Broodstock collected from various islands in Luzon and Visayas were brought to the laboratory, tagged and maintained in raceways and in the field prior to spawning. This paper is a report on spawning (induced and natural) and larval observations on the three species which we have successfully cultured so far, namely *T. maxima, T. squamosa* and *H. hippopus*.

Materials and Methods

Determining Spawning Readiness

Broodstock availability is still the greatest limitation to our culture efforts. In order to preserve the broodstock and allow us a measure of certainty during spawning induction, preselection of ripe clams is done by the biopsy method whereby a small portion of the gonad is removed using a biopsy needle and examined (Crawford et al. 1986). Since the male phase is reached before the female phase (Wada 1952), and induction of sperm release has been found to be relatively easier than eggs for practical purposes, readiness to spawn is gauged primarily by the presence of mature eggs (at least 300/ml of sample) in the gonad. Mature eggs are

those that are spherical to slightly elongate in shape, at least 95–112 μm in diameter and float freely without attached gonad tissues.

Spawning Induction

Induced spawning was done initially with serotonin (2 ml of 0.02 mM in filtered seawater) and then later on with gonad slurry. Both inducers are injected intragonadally. Gonads are obtained from a killed clam, or from one that had recently died. Gonad from one species (*T. squamosa*) has been used to induce spawning in another (*T. maxima*). Biopsy of the gonad has also induced spawning in one instance in *T. squamosa*. Eggs are collected in a bucket and fertilised with sperm from a different individual. The fertilised eggs are then transferred to outdoor raceways with 5 μm filtered seawater.

Spontaneous spawnings were recorded for a mixed batch of *T. maxima* and *H. hippopus*, another of only *T. maxima* and one of *T. squamosa*. The first which was estimated to have occurred at daybreak lasted up to about 1100 hours. The second happened between 1630 to 1700 hours and lasted for about 4 hours while the last took place from 1800 to 2130 hours. Eggs are usually already fertilised and are merely siphoned into nylon sieves of appropriate sizes, washed and transferred into clean raceways with 5 μm filtered seawater. Egg density was maintained at 2–3/ml.

Water temperatures were between 28 and 30°C and salinity at 33–35 ppt for all spawnings.

Larval Rearing

The water was left undisturbed except for periodic samplings until the larvae had reached the D-veliger stage. Except for the batch of *T. squamosa* in which no supplementary food or zooxanthellae was added, the succeeding batches were fed daily with the unicellular alga *Isochrysis galbana* at concentrations of 10^3 to 10^5 cells/ml. Zooxanthellae ($3–4 \times 10^2$) scraped off from pieces of mantles of available clams were also supplied until metamorphosis. *Tridacna squamosa* and *T. maxima* zooxanthellae were used for all batches. Larvae were allowed to settle only on the tank bottom without special substrates.

Excess food and zooxanthellae were flushed out when the water was allowed to flow for about 1 hour every other day. A series of sieves at the outlet retrieved larvae that were carried by the water. Measurements of larval length, height and density were taken daily, if feasible, until the first juveniles appeared. Thereafter, samples of juveniles were taken at random time intervals until harvest.

After metamorphosis, water was allowed to flow through 25 μm filter bags until harvest 3–4 months later. At harvest, the clams were resettled on cleaned coral rubble and eventually transferred to the ocean nursery when they had reached a length of 15–20 mm.

Results

Biopsy and Spawning

Results of spawnings conducted on tagged *T. squamosa* are summarised in Table 1. Biopsies wherein very little gonad was sampled, or if the visceral mass was hit instead, have not been included in the table. Similar data are not available for *T. maxima* as most of the spawners died in the raceways a few days after biopsy or spawning. No repeat spawning has been done on remaining *H. hippopus* broodstock.

The data indicate that although biopsies yielding mature eggs do not guarantee that these eggs will be spawned, the method still provides an indication of the condition of the gonad. With the exception of *T. maxima*, biopsy can thus be used as a basis to eliminate clams with small or spent gonads (i.e. little or no gonad material sampled). Moreover, in nine clams, biopsy alone triggered spawning. *Tridacna maxima*, however, is most vulnerable to injuries during biopsy. Tearing of the mantle and subsequent deaths occurred in 15 broodstock *T. maxima* because of biopsy, and in three other clams also after spawning. One *H. hippopus* broodstock that had a retracted mantle and gaping valves after biopsy also died in the raceways a few days after. Some individuals that appeared weak and were transferred to the ocean recovered. No biopsy- or spawning-related deaths have been noted for *T. squamosa*.

Between serotonin and gonad slurry, intragonadal injections of gonad have proven to be the most effective inducer. Gonad slurry induced egg release in *T. maxima* whereas serotonin did not. For *T. squamosa* (see Table 2) serotonin caused egg release in only one clam, whereas gonad slurry was effective in inducing egg release in six individuals. There is usually a lag time of about 5–15 min after injection of inducer before sperm are expelled. Sperm release continues for about 1.5 hours before eggs are spawned. In cases where sperm release was not profuse and took place for only a short time (5–15 min) eggs were not spawned. The clam merely blew out water from its siphon after sperm release ended. Eggs are spawned from 30 to 60 min.

Tridacna squamosa and *H. hippopus* spawn with vigorous bursts of water from the exhalant siphon so that gametes were propelled upward. For *T. maxima* expulsion of sperm was forceful but eggs were spawned by a gentler oozing out from the exhalant siphon so that a lot of eggs settled on the mantle.

TABLE 1. Spawning record of tagged *T. squamosa* broodstock.

No. of clams	Biopsy result (E, eggs, S, sperm)	Result of spawning induction	Date spawned	Inducer	Other spawning records
1	E S	S	May 86	serotonin	induced 11/86, sperm only
1	- -	E S	May 86	serotonin	induced 11/86 and 11/87, sperm only
3	E S	S	June 86	biopsy	
1	E S	E S	June 86	biopsy	biopsy: ripe eggs and sperm 11/86 (serotonin) and 10/87 (gonad), released sperm only
2	E S	E S	June 86	biopsy	minimal spawning 5/86 by serotonin; eggs biopsied 11/86-eggs and sperm but only sperm released
1	E S	ES	June 86	biopsy	4/86-immature eggs; 5/86 and 11/87: induced with serotonin, sperm only
1	E S	E S	June 86	biopsy	also spawned: 5/86 — few eggs, sperm (serotonin-induced) 11/86 — sperm only (serotonin induced) 12/86 — eggs, sperm (gonad induced) 10/87 — sperm only (gonad induced)
1	S	S	Nov 86	biopsy, gonad	
1	ES	S	Nov 86	biopsy	
1	E S	S	Nov 86	biopsy, gonad	induced 11/87, sperm only
1	S		Nov 86	biopsy, gonad	induced 11/87, sperm only
1	E S	-	Dec 86	serotonin	
1	S	E S	Dec 86	gonad slurry	induced 11/87, sperm only
1	E S	E S	Dec 86	biopsy, gonad slurry	spawned eggs, sperm 5/26; induced 11/87, sperm only
2	E S	E S	Dec 86	gonad	induced with gonad slurry 11/87 — sperm only
1	E S	E S	Dec 86	gonad	17/5/86 spawned by serotonin (minimal) 21/5/86 biopsy; mature eggs/sperm
3	E S	S	Nov 87	gonad	
9	E S	S	Nov 87	gonad	
2	E S	S	Nov 87	gonad	induced 5/87, no reaction

TABLE 2. Record of successful spawnings.

Species	Spawning type	Date	Time	Lunar phase	Tide
T. squamosa	induced (biopsy)	26/06/86	1600–2000	3 days before last quarter	ebb
T. squamosa[a]	induced (gonad)	02/12/86	1400–1630	full moon	flood
T. squamosa[a]	spontaneous	04/05/87	1800–2130	1 day before first quarter	ebb
T. maxima/ H. hippopus	spontaneous	27/02/87	0530–1100	1 day before new moon	flood
T. maxima	spontaneous	06/04/87	1730–2100	first quarter	low water
T. maxima	induced (gonad)	05/11/87	1630–1830	1 day before full moon	flood

[a] Discarded before juvenile stage.

Table 2 shows the record of spawning for *T. maxima, T. squamosa* and *H. hippopus* in which eggs were released. It appears that time of day, tidal cycle, lunar phase and spawning success are not directly linked. The time of the year does not also appear to influence spawning. However, larval survival during the months of November to early February is exceptionally low, most probably because of the cold.

Larval and Early Juvenile Stage

Developmental stages do not differ from those reported for other tridacnid species (LaBarbera 1975; Jameson 1976; Beckvar 1981; Fitt et al. 1984; Murakoshi 1986; Crawford et al. 1986; Alcazar et al. 1987) although the duration of each stage varies to some extent.

Figure 1 (a–e) shows the growth curves of each of

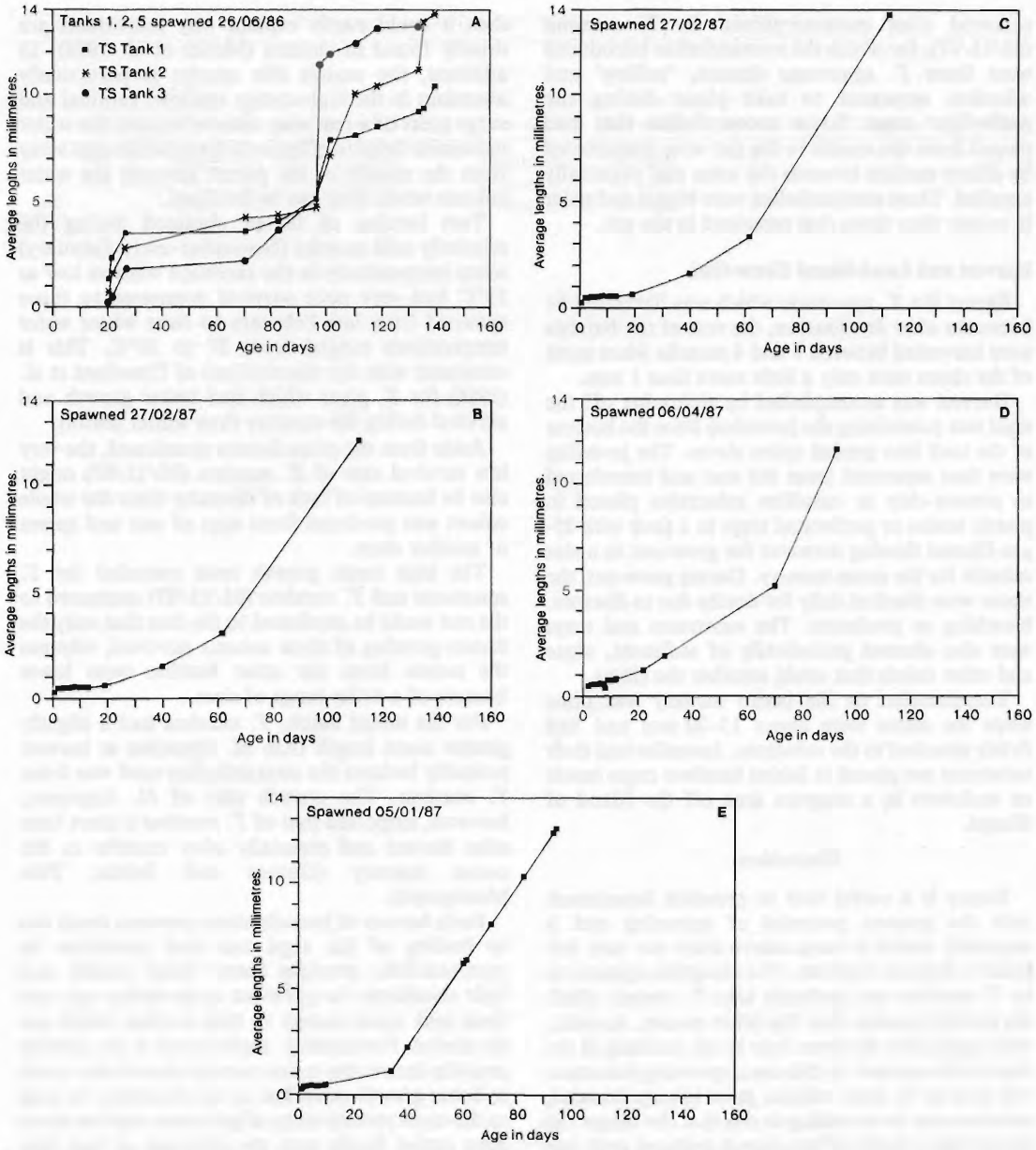

Fig. 1. Growth curves for (A) *T. squamosa*, (B) *H. hippopus*, and (C–E) *T. maxima*.

the spawned batches from the earliest recorded stage up to harvest.

The highest recorded growth rate is that of *T. squamosa* followed by *T. maxima* (05/11/87), the mixed batch of *T. maxima* and *H. hippopus*, and *T. maxima* (06/04/87). The growth curves of the mixed batch were the same until they were differentiated from each other at harvest. It is notable that *T. maxima* was slightly bigger than *H. hippopus* at harvest although the latter is supposedly faster-growing. In terms of survival, *T. maxima* (06/04/87) yielded the greatest number of juveniles at harvest (12 600 juveniles). *Tridacna maxima* (batch 05/11/87) yielded only 135 juvenile clams at harvest.

Zooxanthellae were ingested as early as the veliger stage together with *I. galbana*. The zooxanthellae remained in the gut until establishment of symbiosis

occurred after metamorphosis. In *T. maxima* (05/11/87), for which the zooxanthellae introduced were from *T. squamosa* donors, 'culling' and selection appeared to take place during the pediveliger stage. Some zooxanthellae that had passed from the mouth to the gut were transported by ciliary motion towards the anus and eventually expelled. These zooxanthellae were bigger and paler in colour than those that remained in the gut.

Harvest and Land-Based Grow-Out

Except for *T. squamosa* which was harvested 5–6 months after fertilisation, the rest of the batches were harvested between 3 and 4 months when most of the clams were only a little more than 1 mm.

Harvest was accomplished by siphoning off the algal mat (containing the juveniles) from the bottom of the tank into graded nylon sieves. The juveniles were then separated from the mat and transferred to cement-chip or coralline substrates placed in plastic basins or perforated trays in a tank with 25-μm-filtered flowing seawater for grow-out to a size suitable for the ocean nursery. During grow-out, the clams were checked daily for deaths due to diseases, bleaching or predators. The substrates and trays were also cleaned periodically of sediment, algae and other debris that could smother the clams.

Translocation to the ocean nursery was done when the clams were about 15–20 mm and had firmly attached to the substrate. Juveniles and their substrates are placed in lidded bamboo cages inside an enclosure in a seagrass area off the island of Silaqui.

Discussion

Biopsy is a useful tool to preselect broodstock with the greatest potential of spawning and is especially useful in cases where there are very few mature clams to work on. The exception appears to be *T. maxima* and probably also *T. crocea*, which are notably smaller than the other species. As such, vital organs like the heart may be hit resulting in the death of the animal. In this case, spawning induction will have to be done without prior biopsy. Instead, selection can be according to size (i.e. the bigger the better) and a batch of broodstock induced until one or two spawn eggs. Death due to infection could also be prevented by rinsing the needle in ethyl alcohol and drying it before obtaining a sample. Transfer of induced broodstock to the ocean after spawning appears to hasten recovery and prevent death.

Since gonad slurry has been found to induce spawning even in clams of a different species from the source of the gonad, use of the more expensive serotonin may not be essential any longer.

If the observed spawning behaviour of *T. maxima* is a widespread rather than a localised phenomenon, then it could partly explain why individuals are usually found in clusters (Menez et al. 1988). In addition, the reason this species is particularly abundant in the high-energy shallow, subtidal and surge areas of a reef may also be because the water movement helps to effectively disperse the eggs away from the mantle of the parent towards the water column where they can be fertilised.

Two batches of larvae obtained during the relatively cold months (November–early February) when temperatures in the raceways went as low as 19°C had very poor survival compared to those spawned from late February to June where water temperatures ranged from 27 to 30°C. This is consistent with the observations of Crawford et al. (1986) for *T. gigas* which had better growth and survival during the summer than winter season.

Aside from the other factors mentioned, the very low survival rate of *T. maxima* (05/11/87) might also be because of lack of diversity since the whole cohort was produced from eggs of one and sperm of another clam.

The high mean growth rates recorded for *T. squamosa* and *T. maxima* (05/11/87) compared to the rest could be attributed to the fact that only the fastest-growing of these cohorts survived, whereas the means from the other batches were lower because of a wider range of sizes.

For the mixed batch, *T. maxima* had a slightly greater mean length than *H. hippopus* at harvest probably because the zooxanthellae used was from *T. maxima*. The growth rate of *H. hippopus*, however, surpassed that of *T. maxima* a short time after harvest and especially after transfer to the ocean nursery (Gomez and Belda, This Monograph).

Early harvest of juvenile clams prevents death due to fouling of the algal mat and predation by pyramidellids; provides better water quality and light conditions for grow-out at an earlier age; and frees tank space sooner so that another batch can be started. Presumably, deployment at the earliest possible time to the ocean nursery should also result in better growth rates than in the raceways. As long as the cages prevent entry of predators and the clams have settled firmly onto the substrate so that they are not dislodged or wander away, survival is expected to be higher as well.

Acknowledgments

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Spawning and Larval Rearing of Tridacnid Clams in the Philippines

Sally N. Alcazar*

Abstract

This paper describes the spawning and larval rearing experiments of *Tridacna gigas, T. derasa, T. squamosa, T. maxima, T. crocea, Hippopus hippopus* and *H. porcellanus*. Six of the seven tridacnid species were successfully spawned.

Larvae were reared in concrete tanks, fully exposed to sunlight. They were held for 5–7 days in a static condition, until metamorphosis, then free-flowing water was added to the tanks.

SEVERAL studies have been done on spawning, larval rearing, and growth of the seven species of tridacnid clams (Wada 1954; LaBarbera 1975; Jameson 1976; Heslinga et al. 1984; and Braley 1985). Similar studies were done at Silliman University Marine Laboratory during the past 4 years, including breeding of *T. maxima* (Alcala et al. 1986), *Hippopus hippopus* (Alcazar and Solis 1986), and *H. porcellanus* (Alcazar et al. 1987).

Materials and Methods

Spawning

Two methods of spawning induction were used in the laboratory and in the field: serotonin injected into the gonad (Braley 1985; Crawford et al. 1986) and the introduction of macerated gonad materials into the mantle cavity of the clams near the exhalant siphon (Jameson 1976; LaBarbera 1975; Fitt and Trench 1981; Gwyther and Munro 1981).

The clams were collected from different areas in the Visayan seas. They were either kept in the stocking tanks in the laboratory or placed in cages at the Apo Island reserve.

Often two clams were used in spawning experiments. In the laboratory, spawning induction was done in two 65-l aquaria half-filled with filtered seawater, while in the field spawning was done either in nearshore shallow water or in shallow buckets on board our research vessel. The clams were cleaned by brushing off the epiphytes lodged on the valves. This was done after the clams had been biopsied. Only clams with 50% or more ripe eggs were subjected to spawning induction. As soon as the clams started releasing male gametes, a small amount of sperm was set aside to fertilise the eggs. The clams were allowed to release sperm until the first sign of egg release occurred. The broodstock was later transferred to a 100-l spawning bucket after it had been thoroughly rinsed to remove sperm which stuck to the mantle cavity and at the exterior of the valves. The clams were kept in the bucket until egg release stopped. An aliquot sample of the eggs was taken for microscopic examination to determine the density using the volumetric technique by Castagna and Krauter (1984). Fertilisation of the eggs was done in the bucket by gradually pouring a small volume of sperm until there was a complete mixing of the eggs and sperm. These fertilised eggs were then transferred to the cleaned larval rearing tank. In the field, the fertilised eggs were placed in an aerated 100-l bucket then transported to the laboratory.

Experiments on self-fertilisation were attempted with two species: *T. squamosa* and *H. hippopus*.

Hippopus hippopus sperm were used to fertilise *H. porcellanus* eggs, resulting in a cross between the two.

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Larval Rearing

The larvae were reared in concrete rearing tanks (4 m long × 1 m wide × 0.5 m deep, 1000-l tank), fully exposed to sunlight, and covered with either plastic sheet or a corrugated plastic roofing to exclude rainfall. The stocking density depended on the amount of fertilised eggs in every spawning induction. The larvae were allowed to develop in the rearing tanks in static condition for about 5–7 days, depending on the species used in the experiment, until metamorphosis. Injection of zooxanthellae was done usually on the second day, while feeding (with *Isochrysis*) was optional. Monitoring of the larval development was done daily before the onset of metamorphosis. Free-flowing water was only administered after the larvae metamorphosed.

Results and Discussion

Spawning

Of the seven species of tridacnid clams that have been induced to spawn, only *Tridacna gigas* did not spawn successfully. However, two individuals (52 cm and 48 cm) released sperm during the first attempt to induce them to spawn (Table 1).

Spawning behaviour of the seven species appeared to show the same general pattern described by Wada (1954) except for some variations in *Hippopus hippopus* and *H. porcellanus*. Of the 12 *Hippopus* clams that were induced to spawn, only two individuals showed rhythmical relaxation and contraction of the adductor muscle. Violent expulsion of gametes was seldom observed in *H. hippopus*. Most often, the gametes were released without violent contraction but the exhalant siphon was often erected when the gametes were progressively released and the gap between releases was short (1–2 min intervals). Like *H. hippopus, H. porcellanus* also spawned successfully without violent contraction of the adductor muscle, except that a violent contraction was observed in two clams during the first spawning experiment. This occurred prior to the release of the male gametes.

Release of the male gametes in *Tridacna gigas* and *T. derasa* was similar. Between the first and second expulsion the interval was short, about 2–3 min. Between the second and third expulsion the interval lasted almost 5–10 min. Gametes were released by the slight contraction of the adductor muscle and by the slight movement of the valves. The heavy weight of the valve probably accounted for its limited movement. Violent contraction was seldom observed in these two species, as opposed to *T. squamosa* and *T. maxima*, where violent contraction and movement of the valves was often observed. Being smaller in size and having lighter valves, these two species can easily produce a jerking movement when releasing gametes.

Table 1 shows the record of induced spawning which was conducted both in the laboratory and the field. Serotonin injection was used more often than macerated gonads; gonad material was used only when available.

The temperature at spawning time did not vary much. In the field the temperature ranged from 27 to 31°C.

Of the seven species, *H. hippopus* released the greatest number of eggs. Of the 12 individuals, five released at least 59 million eggs.

Nothing can be said about the relationship between the sizes of the clams and the number of eggs released. None of the species used in the

TABLE 1. Summary of induced spawning in seven species of *Tridacna*.

Species	Induction method used	No. clams that spawned	Temp range (°C)	Latent period sperm released	Latent period eggs released	Approximate no. eggs released/ spawning (millions)
T. gigas	Serotonin	2	27–31 field/lab	30 sec to 1 hour	-	-
T. derasa	Serotonin	6	29–30 field/lab	1–2 min	25–30 min	2.9–12.06
T. squamosa	Serotonin	10	28–31 field/lab	4–92 min	20–60 min	1.4–2.5
T. maxima	Macerated gonad/ Serotonin	6	25–33 lab	2–17 min	25–60 min	2.08–2.90
T. crocea	Macerated gonad/ Serotonin	3	27–30 lab	1 hour	20–73 min	2.1–7.3
H. hippopus	Macerated gonad/ Serotonin	12	25–28 lab	3–90 min	25 sec to 1 hour	21–60
H. porcellanus	Macerated gonad/ Serotonin	6	28–30 lab	5–12 min	15 min	1.08–5.20

TABLE 2. Summary of larval development in six species of tridacnids.

Development stage	Time (days)						
	TD[a]	TS	TM	TC	HH	HP	HH × HP
Fertilised eggs	0	0	0	0	0	0	0
Trochophore	3.5 hours	21 hours	22 hours	17 hours	21 hours	20 hours	9.5 hours
Veliger	15 hours	3	43 hours	36 hours	2	27 hours	27 hours
Pediveliger	5	10	8	8	5	4	4.5
Juvenile (metamorphosed)	7	12	14	11	10	9	10
Egg sizes ($\bar{x}$ ± SD)	104.31 ± 9.46	108.16 ± 8.86	92.77 —	93 ± 7.9	143.50 ± 3.7	116.50 ± 3.7	116.97 ± 9.79

[a]TD, *Tridacna derasa*; TS, *T. squamosa*; TM, *T. maxima*; TC, *T. crocea*; HH, *Hippopus hippopus*; HP, *H. porcellanus*.

experiment exceeded 45 cm except *T. gigas*. The largest *H. hippopus*, considerably smaller in size than *T. gigas* and *T. derasa*, was only 23.3 cm. On two occasions, extrusion of eggs without prior release of sperm occurred in two individuals of *T. derasa* (39 and 42 cm).

On the attempt to cross-breed *H. hippopus* and *H. porcellanus*, 288 000 eggs from the 38-cm *H. porcellanus* were fertilised with sperm taken from one individual of *H. hippopus* (23 cm); about 1000 juveniles survived and were reared in a 1200-l rearing tank.

Larval Rearing

The same larval rearing methodology was used for all species. The larvae were placed in the larval tank in static condition for a number of days and infected with zooxanthellae on the second day.

Comparative larval development of the six species of tridacnids is presented in Table 2.

Of the six species, *T. derasa* showed faster development. The gaps between each stage were short. In *T. squamosa*, the larvae remain longer at the veliger stage. The developmental stages of *T. maxima*, *T. crocea* and *H. hippopus* more or less coincided with the observation of Jameson (1976) and Gwyther and Munro (1981). The chronology of developmental stage in *H. porcellanus* has been described by Alcazar et al. (1987), and larval development in *H. hippopus* and *T. maxima* was described by Alcazar and Solis (1986) and Alcala et al. (1986), respectively. The variability in temperature and of rearing techniques may contribute to the speed of larval development. This is in agreement with observations by Heslinga et al. (1984). But in our case further investigation must be done.

The sizes of fertilised eggs varied in the six species (Table 2). Egg size of *T. squamosa* ($\bar{x}$ = 108.16 μm, SD 8.86) is very close to LaBarbera's (1975) observation which was $\bar{x}$ = 105.3 μm, SD 12.3. The sizes of *H. hippopus* ($\bar{x}$ = 143.5 μm, SD 3.7) and *T. crocea* ($\bar{x}$ = 93.1 μm, SD 7.9) are also very close to Jameson's (1976) observation ($\bar{x}$ = 130 μm, SD 6.3 and $\bar{x}$ = 93.1 μm, SD 3.2), respectively.

A cross between *H. hippopus* and *H. porcellanus* was made for the first time to determine the difference in its growth and survival from that of pure *H. porcellanus*. The larvae were placed in two separate tanks in the same location and received the same amount of sunlight. Their growth and development in early stages were almost identical except that the crossbred larvae spent less time at the trochophore stage and were 1 day behind in metamorphosing.

A 3-month-old crossbred juvenile (4.4 mm) has almost the same external features as does *H. hippopus*, with fine scales at the posterior end of the valves; the shells, however, are paper-thin like that of *H. porcellanus*.

At 5 months old the crossbred juveniles were larger ($\bar{x}$ = 24.05 mm; SD 6.61; n = 20) than the purebred ($\bar{x}$ = 9.2 mm; SD 1.76; n = 20).

Higher growth rate was also observed in cross-fertilised juveniles. Seven-month-old cross-fertilised *T. squamosa* were x = 15.38 mm, SD 2.81, n = 21, while self-fertilised juvenile *T. squamosa* were only $\bar{x}$ = 7.90, SD 2.16, n = 21.

Table 2 summarises the percentage survival of the seven *Tridacna* species. The crossbreed (*H. porcellanus* × *H. hippopus*) seems to show a slightly higher survival rate (2.3%) compared with the others. This is followed by the purebred *H. porcellanus* (1.0%). Between cross and the self-fertilised larvae, cross-fertilised larvae have a better survival rate (13.45%) than the self-fertilised larvae (0.09%).

Conclusion

There are some factors which have to be given special attention, including the viability of the eggs, and the biochemical composition of the water. In general, the larvae still have a very low survival rate.

Better rearing techniques to improve their survival need to be developed.

Acknowledgment

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Selecting Optimum Conditions for Ocean-Nursery Culture of *Tridacna gigas*

J.S. Lucas*, R.D. Braley*, C.M. Crawford and W.J. Nash****

Abstract

Characteristics of the most successful methods for culturing juvenile giant clams through the ocean-nursery phase and best sites are presented. The results of a series of studies with *Tridacna gigas* juveniles at Orpheus Island, Great Barrier Reef, are considered. Four culture methods, suspended subsurface, rack and subtidal and intertidal benthic, were assessed for their convenience and effects on growth and survival. Overall, intertidal benthic culture was superior. Within the intertidal zone, juveniles of *T. gigas* tolerate up to 4 hours daily emersion without adverse effects. Temperature strongly influences rate of growth, with optimum temperature near 30°C. High light intensities are crucial for *T. gigas* juveniles with 90% reduction from full sunlight being lethal. Turbidity is tolerated provided the clams are in shallow conditions without too much light attenuation. *Tridacna gigas* juveniles are adversely affected by persistent disturbance from wave action. It is suggested that giant clams need not be cultured in coral reef areas and that culture in nonreef areas may have the advantage of fewer problems with predators.

THE ocean-nursery phase of culturing *Tridacna gigas* is where juvenile clams are kept in protective containers in the field (Crawford et al. 1988). It extends from when the juvenile clams, at about 20 mm shell length and 9 months old, are transferred into the field from shore-based tanks to when they are over 200 mm, or about 3 years old, and large enough to be in unprotected conditions of the seabed.

The best methods for housing juvenile clams and best sites during this culture phase should have the following characteristics (see also Heslinga et al. 1986):

1. Optimum growth rates of giant clams in shell and tissue, i.e. it is not sufficient to have good increments in shell length if the tissue content (condition) is low;
2. Good survival rates of cultured clams, i.e. good protection from predators, parasites and pathogens, and the absence of stressful environmental conditions;
3. Protective containers that are inexpensive, durable and modular, and which minimise expenditure on maintenance by virtue of their design and location;
4. Sites that give protection from severe storms, poaching and other human interference;
5. Sites that don't detract from other uses of the environment, e.g. navigation, recreation and aesthetic appreciation.

This paper describes a series of studies that have been made at Orpheus Island Research Station (OIRS) to find the optimum conditions for ocean-nursery culture of *T. gigas*. It particularly addresses points 1, 2 and 3, above. While the results are most applicable to the Great Barrier Reef region, they have general implications for site and culture method selection in other geographic regions.

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Culture Methods

Crawford et al. (1988) reported on a study in which four different culture methods were assessed for their effects on survival and growth of juvenile *T. gigas* and for convenience of maintenance and propensity for equipment failures. Two of these methods involved holding the juvenile clams in protective containers above the bottom: on subsurface rafts and subtidal racks. The other two methods involved protective containers fixed to the substrate in the shallow subtidal (3–6 m depth) and intertidal zones. The expected advantages of rearing the clams above the substrate on rafts or racks were improved survival, in that the clams were less accessible to their benthic predators, and improved growth, in that the clams were closer to the surface and high light intensity.

The results of this study are summarised in Table 1. Contrary to the expectation that survival would be improved above the substrate, it was lower in subsurface and rack culture than in benthic culture. This is because heavy infestations of gastropod ectoparasites, pyramidellids, developed on the clams held above the substrate. In limiting access of benthic predators to the clams, the access of predators to their ectoparasites was also reduced and the ectoparasites flourished. Further details of the pyramidellids are provided by Cumming (This Monograph).

TABLE 1. Relative advantages of four methods for ocean-nursery culture of juvenile *T. gigas*: 1 = least favourable to 4 = most favourable. Derived from Crawford et al. (1988).

	Subsurface	Rack	Subtidal	Inter-tidal
Cost of construction	1	2	4	4
Ease of construction	1	2	3	4
Equipment failures	1	4	4	2
Ease of maintenance	1	3	3	4
Degree of fouling	1	2	3	4
Growth rate	1	4	2	3
Survival[a]	1	2	3	4
Pyramidellid infections	1	2	3	4

[a] Excluding mortality from equipment failure.

Intertidal benthic culture was most favourable or equal most favourable in six of the eight assessment criteria listed in Table 1. Overall, intertidal benthic culture was most favourable. A major advantage is that diving is not necessary in construction and maintenance. Construction is easier and there is a further advantage for maintenance through inhibition of fouling growth on the meshes as they are exposed during low tides (note least fouling for intertidal culture in Table 1). The two criteria for which intertidal benthic culture wasn't most favourable were equipment failures and growth rate. The growth rates were marginally less than on racks. Of more significance is the fact that the intertidal position is most exposed to wave action. Some clams were lost from intertidal culture during a severe storm (Cyclone Winifred). It is especially important to have the protective containers securely fastened to the substrate in the intertidal zone.

Tolerance of Emersion

Following this finding of the advantages of culturing *T. gigas* juveniles in the intertidal zone, several studies have been made of the effects of different periods of emersion, reflecting different heights in the intertidal zone. One study found that clams 15 months and older, but not 7-plus months, could survive 10 hours mean daily emersion in a semidiurnal tidal regime. The juvenile clams, however, did not grow under these conditions and their shells showed severe growth interruptions (Lucas 1987; Lucas et al., in press). The clams were able to tolerate up to 4 hours daily emersion without deleterious effects on growth.

A further study of emersion effects using more regular emersion intervals is reported by Nash (This Monograph). This confirms the results of the previous studies and shows a positive effect of limited intertidal exposure on growth rate.

Temperature

Seawater temperature in the bay at OIRS ranges from occasional minima slightly below 20°C in winter to occasional maxima of about 32°C in summer (unpublished data). This natural temperature range provided the opportunity to assess the effects of temperature on growth rate of *T. gigas* juveniles. Juvenile clams being reared in the intertidal zone near OIRS grew from 32 mm mean shell length, at 10 months of age, to 180 mm mean shell length over a 17-month period (December 1985 to May 1987). Their percent increments in shell length, which varied between 2 and 24% per month, are shown against seawater temperature in Fig. 1, indicating a strong influence of temperature on growth rates. Extrapolation of the regression line ($r = 0.61$, $P < 0.02$) gives 19.2°C as the temperature for cessation of growth. However, interpretation of these data in this way needs caution, as the relative increments were greater in the first summer when the clams were smaller.

Upper lethal temperature of *T. gigas* juveniles of ocean-nursery size was about 35°C in short-term tolerance studies (S. Mingoa, unpublished data).

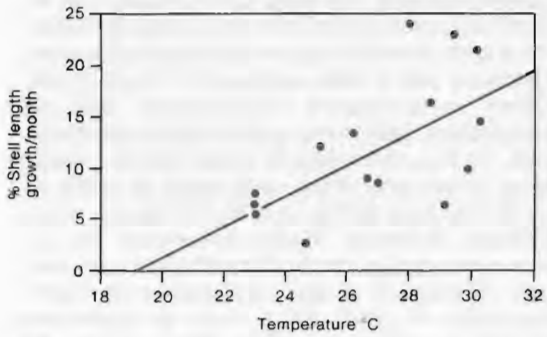

Fig. 1. Percentage growth increment per month in shell length of *T. gigas* juveniles in the intertidal zone at OIRS over the period December 1985 to May 1987 versus mean seawater temperature. The regression line fitted to these data ($r = 0.61$, $P < 0.02$) is: $y = 1.53x - 29.39$.

This upper temperature level was confirmed by two longer-term studies in which juvenile *T. gigas* showed mantle bleaching and death at water temperatures above 35°C. One of these studies is reported by Estacion (This Monograph). The other involved a group of juvenile *T. gigas* sent to Groote Eylandt in the Gulf of Carpentaria, Northern Territory of Australia. These bleached and all died when the seawater temperature rose to >35°C during November 1987 (R. Waldeck, pers. comm.). Bleaching involves loss of zooxanthellae from the clam's mantle tissue. It is interesting that hermatypic corals also lose their zooxanthellae and thus bleach at near lethal high temperatures.

Obviously, all other factors being equal, it is desirable to choose a low latitude locality with consistently high water temperatures about 30°C for rearing *T. gigas*, as the highest annual growth rates should be achieved. In choosing a site, however, the temperature range through all seasons needs to be established. The Groote Eylandt experimental translocation of *T. gigas* juveniles is a cautionary example of a locality where temperature conditions are generally favourable, but during one season are lethal.

Light

Although juvenile giant clams have been reared for several weeks under experimental conditions without zooxanthellae (Fitt et al. 1984), no natural tridacnids have been found without zooxanthellae and the accumulated evidence is that they are highly dependent on their symbionts for nutrition. Small juveniles of *T. gigas* lose condition within a few days in darkness and die after a week or so in darkness (Mingoa, This Monograph).

Juveniles of *T. gigas* were kept in a seawater system at OIRS under full sunlight, 50% shading and 90% shading. Those under full sunlight and 50% shading showed similar growth and survival. Those under 90% shading showed poor growth and heavy mortality, so that only 16% survived after 3 months (Lucas et al., in press). Irradiance level under the 90% shading was recorded at 298 $\mu E/m^2/sec$ at noon on a clear sunny day. This is above the irradiation level of 200 $\mu E/m^2/sec$ to saturate the photosynthetic capacity of 15–20 mm shell length juveniles found by Mingoa (This Monograph), but below the level of about 600 $\mu E/m^2/sec$ found for similar small juveniles by Fisher et al. (1985).

The poor survival and growth of *Tridacna gigas* juveniles under 90% shading suggest that irradiation levels of at least 300 $\mu E/m^2/sec$ must be sustained for a substantial period on most days if light isn't to be a limiting factor in growth rate. More rigorous studies are required of the irradiation levels and durations to saturate the growth capacity of these juvenile clams.

Turbidity and Wave Action

The locality where most of these studies were conducted is Pioneer Bay on the western side of Orpheus Island, facing the mainland. In this aspect there is protection from the prevailing easterly winds and seas, but the water is turbid and underwater visibility is generally about 5 m. The eastern side of the island faces the Great Barrier Reef. It is much more oceanic, with relatively clear water and greater coral diversity than the western side of the island (J. Veron, pers. comm.). The eastern side is, however, subject to frequent strong wave action.

Juveniles of *T. gigas* were cultured in the intertidal and subtidal zones on a fringing reef on the eastern side of Orpheus Island to compare their growth and survival rates with those in Pioneer Bay. The result was that both survival and growth were poorer on the eastern side. This was apparently caused by the regular disturbance of clams by strong wave action (Lucas et al. 1988). Reflecting this disturbance, their thin shells were regularly chipped and the clams were pushed against the inshore edges of the protective trays. Also clam growth was more retarded in the intertidal zone, where wave action was strongest.

It is notable that the culture method where clams were most disturbed produced the poorest growth rates (Crawford et al. 1988). This was suspended subsurface culture (Table 1). The trays and clams experienced movement through wave action on the floats from which they were suspended. It is also possible that the poor growth resulted from pyramidellid infestations (Cumming, This Monograph), which were heavy in this culture method (Table 1).

These results for the adverse effect of regular

disturbance on giant clam growth are indicative rather than conclusive at this stage.

A further point from the comparative growth at the silty site versus an oceanic site is that silt per se does not inhibit clam growth, at least at moderate levels. Silt, however, will affect the clams in that it reduces light penetration. Heavy mortality was experienced at a subtidal site, about 5 m depth, in Pioneer Bay through low light levels resulting from a combination of depth, turbidity and fouling of protective meshes (unpublished data). Siltiness need not be a contraindication of a good ocean-nursery site for *T. gigas*, provided the clams are kept sufficiently shallow for good light penetration (see also Barker et al., This Monograph).

Are Coral Reefs Necessary for Giant Clam Culture?

Lucas et al. (in press) considered this question. They suggested that the particular feature of coral reefs that is important to juvenile giant clams is the coral reef's complex three-dimensional structure. This structure, such as within staghorn coral (*Acropora*) thickets, satisfies two conflicting needs of juvenile giant clams: the need to be exposed to high levels of sunlight while needing to remain cryptic and hidden from predators. Lucas et al. (in press) concluded that giant clam juveniles can be cultured in tropical marine environments away from coral reefs, provided they are given protection from predators and a hard substrate for attachment. Other environmental requirements such as temperature, light, water quality, etc., must also be met. In fact, there may be advantages in rearing giant clams away from coral reefs, in terms of predation. Apo Island, central Philippines, where Silliman University Marine Laboratory has an ocean-nursery site, is a locality with high coral cover and diversity. It is also characterised by heavy mortality of giant clams, even in protective containers (Estacion, This Monograph). In nonreef habitats there are fewer kinds of predators and therefore fewer potential predators of the cultured clams. The development of a giant clam ocean-nursery site within a large seagrass area near Silaqui Island, northern Philippines, by researchers of University of the Philippines Marine Science Institute is an example of using a nonreef habitat (Belda et al., This Monograph).

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Reproductive Cycles and Mariculture of Giant Clams in Papua New Guinea

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Abstract

Information on the extensive mariculture of clams at Motupore is presented together with results from Madang. Since 1983 four species have been successfully spawned and reared, and 4-year-old *T. squamosa* and *T. gigas* are now unprotected on a reef grow-out site. Results of monthly biopsy of broodstock show that *T. gigas* has no seasonality whilst *T. squamosa* shows peak egg production in August. Data on growth under different conditions and on clam parasites are presented.

In recent years interest in the mariculture of giant clams (family Tridacnidae) has increased to encompass much of the Pacific. With an increase in the number of institutions involved in giant clam mariculture basic knowledge of methods and clam biology has increased dramatically.

As part of an international project, funded by the Australian Centre for International Agricultural Research, the University of Papua New Guinea carried out research on giant clam mariculture from 1984 to 1987. The mariculture work was carried out at the university's Motupore Island Research Centre, 15 km east of Port Moresby, located in Bootless Bay. The research station provided the infrastructure for the project and a base from which field work could be undertaken. Previous work on the reproduction of giant clams at Motupore Island is reported by Gwyther and Munro (1981) and Munro and Gwyther (1981). The following report is intended as an overview of reproduction and growth of tridacnid clams at Motupore Island as detailed results will be presented elsewhere.

All species of giant clams, with the exception of *Hippopus porcellanus*, occur in Papua New Guinea. In many areas, especially around densely populated urban centres, all but *Tridacna crocea* are difficult to find. Tridacnid clams continue to be a prized food item among local people. In addition, clam poaching is known to occur amongst the sparsely populated islands in the Louisiade Archipelago.

Five species of tridacnid clams occur in the Bootless Bay area: *Tridacna gigas*, *T. squamosa*, *T. maxima*, *T. crocea* and *Hippopus hippopus*. All species were spawned successfully, with the exception of *T. maxima*, which was not attempted. Annual reproductive cycles were studied for two species, *T. gigas* and *T. squamosa*, over a period of 20 months. Growth of juvenile clams was monitored in relation to various environmental factors, in tanks and in the field. In addition, *T. squamosa* were also reared at the Christensen Research Institute in Madang, on the north coast of PNG.

Study Sites

Water temperatures in Bootless Bay range from a high of approximately 30°C in the summer to a low of about 24.5°C for about 3 months in the winter. Motupore Island is located about 0.5 km offshore, surrounded by a fringing reef on the north and east side and a shallow lagoon and reef crest on the south and west (windward during trade winds) side. A submerged barrier reef is 8 km offshore with more oceanic water.

Four study sites were used. A holding pen for field-collected clams, set up in the 1970s by J.

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Munro and J. Gwyther, was located on the north fringing reef adjacent to Motupore, on the inshore side of the island. The pen is exposed at extreme low tides and has a maximum depth of about 2.5 m at high tide, with water visibility of usually less than 7 m. The ocean-nursery site was located on the south side of Motupore Island behind the reef crest in the lagoon. The substratum was sand with sparse seagrass and the site had a mean depth of 3 m. The field biopsy site was located on the south reef of Loloata Island, adjacent to Motupore Island. The depth of the reef varied between 3 and 8 m. Visibility was generally higher at this site than on the inshore sides of the islands. The fourth site was a temporary ocean-nursery site, located on the lagoon side of the barrier reef (Horseshoe Reef). Average depth was 3 m and visibility was generally greater than 15 m. During the summer the wind was northwesterly and this site was exposed to heavy surge.

Mariculture Facilities

Tanks already existing at Motupore Island were initially used for clam mariculture, including 2600-l fibreglass pools. In addition, rectangular raceways were constructed out of fibreglass on plywood in two sizes: 50 cm deep (900 l) and 25 cm deep (450 l).

Clam mariculture tanks were supplied with seawater pumped from the north Motupore fringing reef, 250 m off the laboratory. An 80-mm PVC intake line (250 m length) provided 150 l/min output flow from the pump. Tanks could be fed unfiltered water from a header tank, or water filtered through a commercial sand filter, direct from the pump. A variety of invertebrate larvae did pass through the sand filter, as organisms often settled in the tanks. Water flowed through the tanks for 14 hours daily; pumps were not run at night when the generators were turned off.

Results

Reproductive Cycles

The reproductive state of individual clams was determined by gonad biopsy, similar to the methods of Braley (1985). Approximately 39 *T. squamosa*, which were field-collected and located in the holding pen, were biopsied monthly for a period of 20 months. A mean number of 18 *T. gigas*, also located in the pen, were biopsied monthly. In addition, a mean of 11 *T. gigas* naturally occurring on the south Loloata reef were biopsied monthly for 14 months. Presence or absence of eggs and the egg density of the biopsies were used to categorise the reproductive state of individual clams.

There was no spawning peak for *T. gigas* on the south Loloata reef, as one or more ripe individuals could be found during most months. *Tridacna gigas* located in the pen did not show a peak period of egg development during any season. *Tridacna squamosa*, on the other hand, showed an increase in egg development during August, September and October for two consecutive years, with a spontaneous spawning occurring in early September during a third year. Detailed results will be published elsewhere.

Larval Rearing Techniques

Extensive larval rearing techniques were used at Motupore Island. Initially this entailed the larvae being reared in the same tank of water from egg to metamorphosed juvenile. Yeast extract at a concentration of 1 μg/ml tank water (Fitt et al. 1984) was used to feed the veligers for approximately 5 days. In other instances larvae were not given an external food source, but fed on the natural phytoplankton present, if any, in the tank water. The reliability of both feeding methods was poor, as survival of different batches of clams was inconsistent. Yeast extract almost invariably created dense phytoplankton blooms of a filamentous diatom, where veligers were mechanically caught up in the algae and not able to survive. When relying on natural phytoplankton blooms veligers usually starved.

A more successful larval-rearing method was employed subsequently. Upon reaching the D-veliger stage, larvae were pumped out of the tanks with a submersible pump and caught in a sieve, then transferred to fresh, 5-μm filtered water. This helped to separate the healthy larvae from the dead eggs and dying larvae. These larvae were then fed daily with 1 l of a moderately dense culture of *Isochrysis galbana* for approximately 5 days. Survival using this method was more reliable than those mentioned above and food uptake was consistently seen.

Once pediveligers were observed, zooxanthellae (*Symbiodinium microadriaticum*) scraped from the mantle of an adult conspecific clam was added to the larval tank daily. The earliest zooxanthellae uptake was observed in 7-day-old *H. hippopus*; usually zooxanthellae uptake occurred on day 9, coinciding with metamorphosis.

At this point it is important to understand that water quality and the natural availability of food may differ significantly between geographic locations. At Motupore Island, relying on natural phytoplankton for larval food gave inconsistent results, while feeding with *I. galbana* gave the most consistent survival. Though Heslinga (1986) and Heslinga and Fitt (1987) state that the Wells-Glancy method of natural phytoplankton production

TABLE 1. Mean sizes of juvenile tridacnid clams in original rearing tanks, up to approximately 6 months of age. Note the two tanks of *H. hippopus* are from the same spawning.

Date spawned:	*T. gigas* 17 Apr 86	*H. hippopus* 29 Apr 86	*H. hippopus* 29 Apr 86	*T. gigas* 30 Jul 86	*T. squamosa* 10 Sep 86	*T. crocea* 10 Sep 86
Age (days)						
23	-	-	-	-	325.8μm	288.1μm
25	434μm	-	-	-	-	-
28	-	347.6μm	314.4μm	358.3μm	-	-
33	-	-	-	436.7μm	-	-
42	-	420.2μm	397.9μm	-	-	-
43	-	-	-	-	686.7μm	-
44	-	-	-	-	-	476.3μm
54	-	-	-	591.8μm	-	-
64	978.3μm	-	-	-	-	1.1 mm
69	-	-	-	-	2.0 mm	-
75	-	1.2 mm	948.1μm	-	-	2.8 mm
82	-	-	-	-	3.0 mm	-
85	1.75 mm	-	-	-	-	-
86	-	-	-	1.2 mm	-	-
96	-	-	-	2.6 mm	-	-
123	-	4.1 mm	3.3 mm	-	-	-
124	-	-	-	5.4 mm	-	-
138	6.2 mm	-	-	-	-	-
160	-	11.5 mm	8.3 mm	-	-	-
173	11.5 mm	-	-	-	-	-
197	-	15.3 mm	-[a]	-	-	-
216	-	16.5 mm	-	-	-	

[a] Two tanks of *H. hippopus* combined.

provides sufficient larval food, it should be stressed that although this is a reliable method for larval rearing in Palau, it may not be a suitable method in other locations where water conditions differ. Certainly Palauan conditions are more oceanic than, for example, Motupore Island or Madang, where the influence of New Guinea land mass is significant.

Juvenile Growth Rates in Tanks

Mean sizes of juvenile clams in rearing tanks (< 1 year old) are summarised in Table 1. The results are comparable to growth rates obtained by other researchers. It was not uncommon, however, to observe batches of juvenile clams whose growth was obviously stunted, or slower than normal. One might attribute this to a genetically inferior batch. However, when these animals were subsequently moved to a different tank where clam growth was consistent with normal values, the stunted animals were able to recover and resume a more normal growth rate after 30–60 days. In come cases significant mortalities accompanied the growth slowdown.

The causes of the unsuitable microenvironments in the tanks are not known. In some cases the tanks have excessive macroalgae growth, which is thought to deplete nutrients in the water needed by the clams and their zooxanthellae, but it is not always present when growth is stunted. Often the appearance of healthy and unhealthy tanks will be quite similar, and healthy tanks may contain abundant amounts of macroalgae. As it can dramatically affect the growth and survival of juvenile nursery clams, this problem deserves further study.

Comparison of Clam Growth in Tanks and Field

The effects of water depth and position relative to the inlet and outlet ends of raceways on growth of 7.5-month-old *T. gigas* (mean size 35.2 mm ± 6.2, $n = 160$) was experimentally tested, and growth of clams in raceways was compared with that of individuals in the field. After 5 months there was no significant difference in growth rates between clams in the inlet and outlet ends of either the deep (50-cm) or shallow (25-cm) raceways. There was a significant difference in growth of clams between the two raceways. At 3.5 months after initiation of the experiment, clams in the deep raceway were larger (mean 57.4 ± 10.5 mm, $n = 79$) than those in the shallow raceway (mean 57.4 ± 9.0 mm, $n = 80$). The magnitude of the differences increased with time.

In view of the stunting of young juveniles in tanks mentioned earlier, it is important to note that after about 4 months, growth rates of these experimental

clams declined markedly, from a high of 0.372 mm/day to a low of 0.086 mm/day in the deep raceway. Half of the deep raceway animals were transferred to the 3-m depth south Motupore ocean nursery site at 5 months; 2 months following this transfer the field clams were significantly larger (mean 80.3 ± 10.2 mm, $n = 39$, 0.254 mm/day) than those remaining in the deep raceway (mean 71.2 ± 14.8 mm, $n = 38$, 0.050 mm/day). The ability of clams transferred to the field to assume normal growth rates is evident. An identical situation was observed when half the animals in the shallow raceway were moved to the 3-m depth field site, recovering to normal growth rates after about 60 days.

Effect of Depth on Growth Rates in the Ocean Nursery

The effect of water depth on the growth of *T. squamosa* was experimentally tested at the ocean-nursery site. Triplicate samples ($n = 30$ each, mean size 23.7 ± 4.0 mm) of 1-year-old clams were placed at four sites on the south Motupore reef; 3 m depth sandy bottom with sparse seagrass behind the reef crest (ocean nursery site), and 6, 9 and 12 m depth outside the reef crest on the reef slope. Clams were measured monthly. At 2 months clams at the 6 m site were infested with pyramidellids (see below for further discussions) and this site was abandoned after 3 months.

At 2 months a significant difference ($P < 0.001$) was found among sites, with growth rate decreasing with increasing depth. Differences in growth among sites increased with time. At 5 months mean sizes of clams at sites 3, 9 and 12 m were 53.4 ± 9.0, 36.9 ± 10.4 and 29.0 ± 5.8 mm, respectively. At this time two trays from 9 m and two trays from 12 m were transferred to the 3-m site. The transferred animals showed an immediate increase in growth rate, equivalent to that of the original 3 m depth animals, and after 2 months the transferred animals were significantly larger than the remaining clams at the respective depth. Light intensity was nine times more intense at 3 m than at 9 m depth.

Mortality was over 50% at the 12-m site, but was approximately 7% at both the 3- and 9-m sites. Pyramidellids were not found at these three sites. Mortality from pyramidellids at the 6-m site was 100% over a 2-month time period.

An additional experiment was run to retest the difference in growth between clams at the 3- and 6-m depth. *Tridacna squamosa*, approximately 2 years old, were placed at the 3-m ocean nursery (mean size 87.7 ± 8.5 mm, $n = 24$) and at a new 6-m site on a sandy bottom outside the reef crest (mean size 85.1 ± 6.5 mm, $n = 22$). For the first few months there was no significant difference in growth between the two groups. By 6 months the animals at 3 m were significantly larger than those at 6 m (mean size 106.6 ± 11.5 mm, $n = 24$ vs 98.5 ± 9.4 mm, $n = 22$, $P < 0.02$).

A different set of *T. squamosa* was split between three sites: 3-m south Motupore lagoon, 6-m south Motupore reef and 3-m barrier reef (Horsehoe Reef). The barrier reef was located 8 km offshore and had consistently clearer, more oceanic water, but was less sheltered from wave action. Over the long term (10 months) the animals at the 3-m depth were significantly larger than those at 6 m. Growth of clams was not appreciably different between the two 3-m depth sites. Mortality was slightly higher at the barrier reef site, however, and edges of shells were obviously chipped and worn from repeated contact among clams due to movement from wave action.

Results from our experiments indicate that light intensity is an important factor when choosing an ocean-nursery site. It follows that water depth and clarity are critical factors. Unprotected sites with heavy wave action and surge should be avoided, as they appear to negate the benefit of the clearer, more oceanic water. Details of experiments on growth rates of clams under different environmental conditions will be published elsewhere.

Tridacnid Clam Parasites

As mentioned above, 90 1-year-old *T. squamosa* involved in a single experimental site (at 6 m deep) experienced 100% mortality over a 2-month period. Unidentified pyramidellid parasites were found on these animals, but not removed from clams during these 2 months. Pyramidellids were also occasionally found on other ocean nursery clams (*T. squamosa* and *T. gigas*). They were kept under control by manually removing and destroying the parasites.

When large (4–5 mm length) pyramidellids were found, egg masses were often also found on the underside of the clams. These were destroyed, usually by scrubbing the clams with a stiff toothbrush. Although pyramidellids periodically reappeared, the above methods seemed adequate to keep them under control in the field.

Clams maintained in raceways were also infected by pyramidellids. It is important to note that water entering raceways first went through a sand filter, which did not filter out all mollusc eggs and larvae. Mortality in raceways was high, about 50%. Once again the parasites were manually removed, and either brushed or sprayed with a high-pressure hose to remove any eggs or tiny juveniles. Only a single unidentified species of pyramidellid has been observed.

One additional gastropod predator (*Cymatium muricinum*) was found in clam trays at the ocean-

nursery site (Perron et al. 1985). Juveniles were found on many occasions and manually removed. In addition, several large juveniles or adults were found in the process of eating the clam. These parasites do not appear to be capable of causing mass mortalities of clams.

Growout Phase

Tridacna squamosa, 115–130 mm long (age 34 months), exhibited 100% survival when taken from cages and set on open bottom at the ocean-nursery site. Subsequently, *T. squamosa* greater than 150 mm and *T. gigas* greater than 160 mm also exhibited no mortality when removed from cages.

Tridacnid Clam Rearing at Madang

Six species of tridacnid clams occur in the Madang area on the north coast of Papua New Guinea. These include the same five that occur around Motupore Island, together with *T. derasa*. Giant clams of most species on the reefs around Madang town have been heavily fished, with only *T. crocea* locally common and apparently not eaten. Of species eaten, *T. squamosa* and *T. maxima* are the easiest to find, averaging one clam per hour of underwater search. *Tridacna gigas* are much less common and those that were found were small (< 50 cm) and not yet females, precluding any collection of female broodstock. *Hippopus hippopus* and *T. derasa* are rare.

Twenty-five *T. squamosa* were collected for broodstock and maintained on Gosem Reef adjacent to the Christensen Research Institute. The animals were biopsied in April, July, September, October and November 1986. Only one clam appeared to be ripe in April, however it could not be induced to spawn eggs. Several ripe females were found during winter and spring months, indicating a comparable spawning season to that of *T. squamosa* at Motupore Island.

In October 1986, *T. squamosa* were induced to spawn using serotonin. The mean size of juveniles at 6 months was 14.8 ± 4.6 mm $n = 156$. Two ocean-nursery sites were set up, one 6 m deep (Gosem Island) and one 3 m deep (Kranket Lagoon). Growth rates of 0.15–0.21 mm/day were comparable to those obtained for *T. squamosa* reared at Motupore Island.

Conclusions

At Motupore Island, *Tridacna gigas* did not appear to have an annual reproductive cycle, as ripe females could usually be found year-round. *Tridacna squamosa*, on the other hand, did show an annual spawning season, from around July through October. Ripe females could be found in Madang during these same months. However, our data are not complete enough to determine whether spawning also occurred in the warmer months at Madang. Differences in water temperature between summer and winter in Madang are not as extreme as on the south coast of PNG.

The importance of familiarity with local seawater conditions for obtaining natural phytoplankton for larval food cannot be overemphasised. Different marine conditions at different geographic locations may affect results of larval feeding experiments and provide results which are not consistent with those already published for other locations. This effect needs to be carefully evaluated in investigations of larval survival in different experimental conditions.

Knowledge of unsuitable microenvironments which develop in mariculture tanks, and result in very low growth rates and increased mortality, is an important area for future investigation. The demonstrated ability of clams to recover once transferred to a suitable environment is critical to obtain optimum growth rates of animals. This suggests the importance of transferring animals maintained in tanks to an ocean-nursery site as soon as practical.

The effects of mariculture tank design on growth of juvenile clams should be considered. Our results indicated deep (50-cm) raceways provided an environment which gave faster growth when compared to shallow (25-cm) raceways.

Selection of a good ocean-nursery site is important in obtaining optimal growth of juvenile clams. Considering submarine environments, maximal growth rates over the long term are obtained at a depth of 3 m. Growth rates decline with increasing depth. Visibility must also be taken into account when choosing a depth, as it influences the light penetration. The benefits of clearer water must be weighed against the negative effects of surge in exposed areas. In addition, when choosing an ocean-nursery site consideration of the local human community is essential. One should avoid placing animals where curious individuals or fishermen might interfere with them, or where they are occupying a 'private reef' without the owner's permission.

The importance of monitoring both tank-maintained and ocean-nursery clams for parasites, both pyramidellids and *Cymatium muricinum*, cannot be overstressed. Pyramidellid infestations have the ability to cause mass mortality, especially in younger clams (1 year or less), in short time periods.

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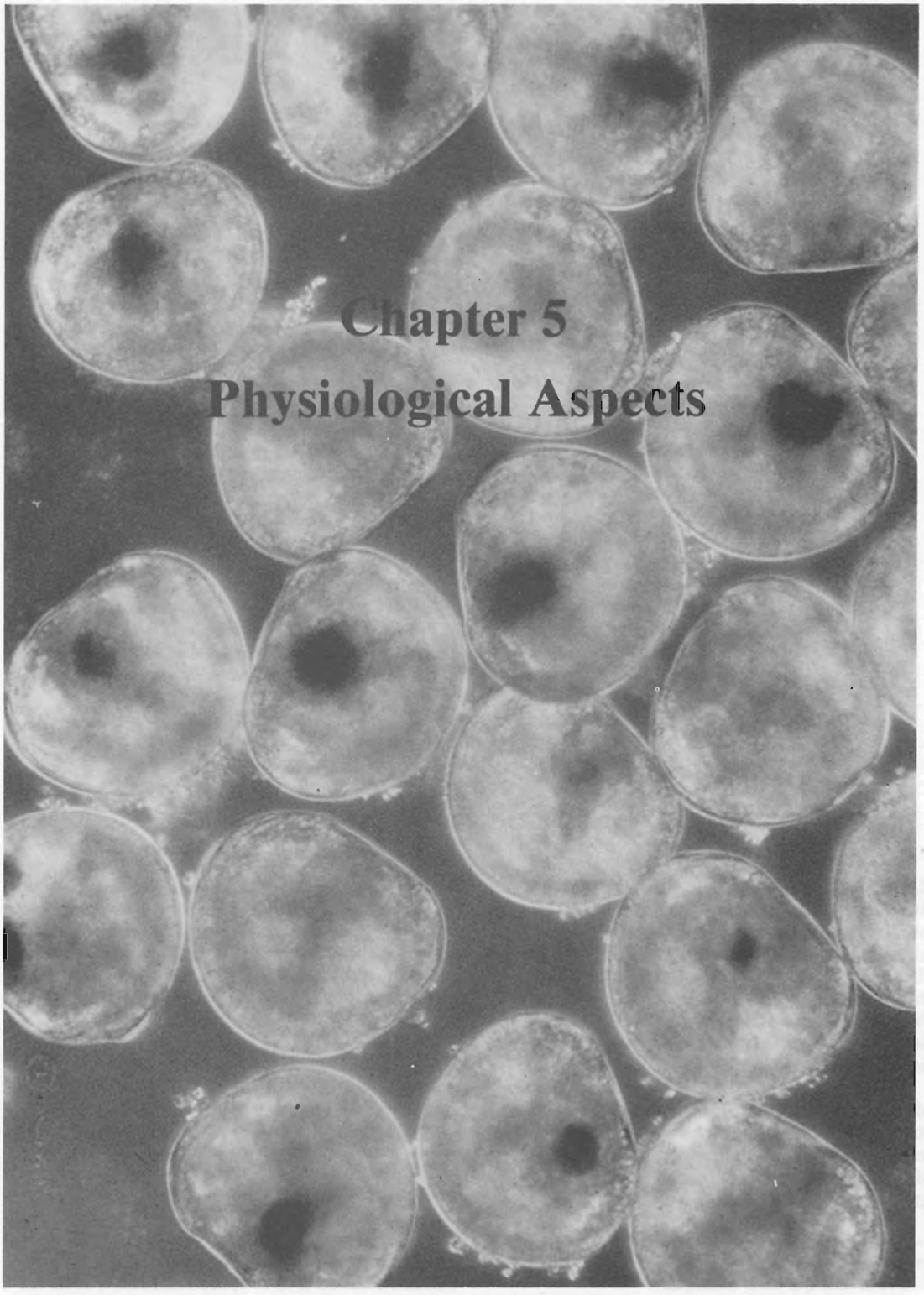

Chapter 5
Physiological Aspects

Biochemical Development and Energetics of *Hippopus hippopus* Larvae

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Abstract

The biochemical composition of fed and starved larvae of *Hippopus hippopus* was determined throughout development using a microanalytical scheme.

Total organic matter increased during development from fertilised eggs to day 10 pediveliger, but decreased during settlement from day 10 to day 14. Ash content increased from 29.03% in fertilised eggs to 75.0% in day 10 pediveligers. Ash content further increased through settlement to 86.39% on day 14.

Lipid and protein levels increased during development from fertilised eggs to day 10, while carbohydrate levels remained relatively low and constant during this period. In excess of 60% of the total organic matter in fertilised eggs was composed of lipid, and this high level was maintained throughout larval development to settlement. On settlement, lipid levels decreased sharply from 69.05% to 29.16% on day 14, with a corresponding increase in protein from 26.38% to 64.58% during the same period.

During short periods of starvation, the major proportion of both the weight and caloric losses were due to lipid. Protein was utilised during starvation of 3-day-old larvae for 3 days, but increased during starvation of older (6–9 days) larvae. Carbohydrate levels remained low, and changed little during starvation.

Lipid was the major energy reserve of larvae and the energy source for settlement and metamorphosis.

LITTLE information is currently available on the biochemical development of bivalve larvae. Of the studies that have been undertaken, most have been concerned with oyster larvae (Holland and Spencer 1973; Bartlett 1979) and the larvae of wood-boring bivalves (Mann and Gallager 1984, 1985). It is believed that the biochemical development of the larvae of a tropical bivalve has not previously been investigated.

Biochemical analysis of larvae throughout development allows the importance of each biochemical fraction and the major energy reserves to be determined. Biochemical data are of value in determining nutritional requirements and the physiological state of the larvae.

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This paper describes the biochemical development of *Hippopus hippopus* larvae through to settlement and early post-metamorphosis. Short periods of enforced starvation were carried out to determine the principal energy reserve during larval development.

Materials and Methods

Adult *Hippopus hippopus* were induced to spawn following intragonadal injection of 2 mmol serotonin (Braley 1985). Eggs were fertilised, and larvae were maintained under conditions described by Crawford et al. (1986). All larval samples for analysis originated from the same spawning. Samples were prepared for analysis by isolating larvae on a 53-μm mesh sieve, and rinsing with 0.45-μm filtered seawater and isoosmotic ammonium formate solution (3% w/v) in succession. The larvae

were then rapidly washed into a small vial prior to freeze-drying. Samples of fertilised eggs were prepared for analysis in similar fashion. Dried samples were stored in sealed vials in a desiccator until analysis. Larval samples were taken at 21, 30 and 48 hours after fertilisation and then at 2-day intervals until day 14. Small samples were also taken at each interval and preserved in seawater: formalin (4% v/v) for subsequent measurements. Batches of larvae which were unfed between days 3–6 and 6–9 were sampled in a similar way.

For biochemical analysis, between 5 and 10 mg of freeze-dried sample was homogenised in a glass tissue grinder with 1.0 ml distilled water. Homogenates were analysed for total carbohydrate, total lipid and protein by a modification of the method described by Holland and Gabbott (1971) and Holland and Hannent (1973). The modification was that protein was determined by the Folin-phenol reaction of Lowry et al. (1951), as described by Mann and Gallager (1985), and not as protein nitrogen. Each analysis was conducted in duplicate and mean values calculated.

Ash content of each sample was determined as that remaining after heating at 450°C to a constant weight. Larvae were weighed on a Cahn 21 Automatic Electrobalance.

Caloric content of the larvae throughout development was estimated, indirectly, from the biochemical composition. Caloric equivalents of 9.45, 5.65 and 4.1 cal/mg for lipid, protein and carbohydrate respectively were used for the calculation (Crisp 1971).

Results

The mean values for shell dimensions, dry weight and biochemical composition of fed and starved larvae throughout development are shown in Table 1. Biochemical composition and calculated energy contents are given in Table 2. The level of total organic matter (expressed as μg/mg ash-free dry weight, AFDW) increases during larval development from a value of 172.05 μg/mg AFDW for fertilised eggs to 327.83 μg/mg AFDW on day 10 prior to settlement. The value then decreases through settlement and metamorphosis to 153.49 μg/mg AFDW on day 14. A corresponding increase in the percentage of ash (mainly shell) is evident through larval development from 29.03% for fertilised eggs to 75.0% on day 10. Ash content continued to increase to a value of 86.39% for day 14 samples.

Changes in Biochemical Composition

The changes in the levels of protein, lipid and carbohydrate (μg/mg AFDW) during larval development are shown in Fig. 1. Lipid levels are shown to rise steadily during larval development from 103.42 μg/mg AFDW for fertilised eggs to 226.39 μg/mg AFDW on day 10. Protein levels show a similar pattern and rise from 49.88 μg/mg AFDW for fertilised eggs to 86.5 μg/mg AFDW for day 10 larvae. Carbohydrate levels remain relatively low during larval development with values of 18.75 μg/mg AFDW for fertilised eggs and 15.10 μg/mg AFDW for day 10 larvae.

TABLE 1. Shell dimensions, dry weight and biochemical composition of fed and starved larvae throughout development.

								Biochemical Composition (μg/mg AFDW)		
Age (days)	Days fed	Days starved	Mean length (μm)	Mean height (μm)	Dry Wt (μg/larva)	% Ash	Ash free dry wt (μg/l)	Total carbohydrate	Total lipid	Protein
0	0	0	122.4	-	ND*	29.03	ND	18.75	103.42	49.88
0.875	0	0	131.52	113.28	ND	11.11	ND	4.85	126.11	34.72
1.25	0	0	170.61	151.79	0.16	19.23	0.13	8.61	143.14	73.05
2	0	0	175.26	149.40	0.55	38.23	0.34	6.87	143.91	71.34
4	1	0	187.04	158.32	0.77	58.24	0.32	10.77	173.07	51.43
6	3	0	193.34	164.06	0.90	69.09	0.28	17.31	204.21	103.43
8	5	0	194.00	165.78	0.92	68.96	0.28	15.10	169.91	88.80
10	7	0	194.49	166.00	1.00	75.00	0.25	14.94	226.39	86.50
12	7	0	196.00	166.12	ND	87.17	ND	21.08	116.35	134.53
14	7	0	198.66	166.33	ND	86.39	ND	9.59	44.77	99.135
6	0	3	193.48	162.24	0.80	61.53	0.30	12.52	94.85	51.90
9	3	3	196.56	163.6	0.82	66.87	0.27	10.35	184.28	116.54

*ND not determined.

TABLE 2. Biochemical composition and caloric content of *H. hippopus* larvae throughout development.

Age	Days fed	Days starved	Biochemical content (μg/larva) Carbohydrate	Lipid	Protein	Caloric content (cal/larva) ($\times 10^{-4}$)	Caloric content (cal/mg AFDW)
0	0	0	ND*	ND	ND	ND	1.33
0.875	0	0	ND	ND	ND	ND	1.40
0	0	0	1.15	19.26	9.83	2.42	1.80
2	0	0	2.35	49.33	24.45	6.13	1.79
4	1	0	3.47	55.84	16.59	6.35	1.97
6	3	0	4.84	57.20	28.97	7.24	2.58
8	5	0	23.65	48.68	25.44	7.00	2.16
10	7	0	3.73	56.59	21.62	6.72	2.68
12	7	0	ND	ND	ND	ND	1.94
14	7	0	ND	ND	ND	ND	1.02
6	0	3	3.85	29.19	15.97	3.81	1.24
9	3	3	2.82	50.27	31.79	6.66	2.44

*ND, Not determined.

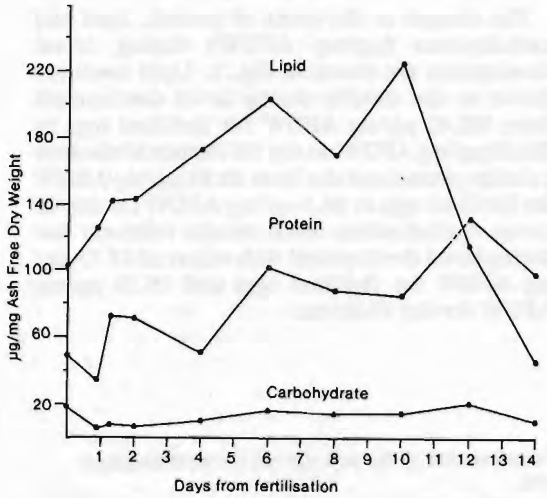

Fig. 1. Changes in lipid, protein and carbohydrate levels during larval development of *Hippopus hippopus*.

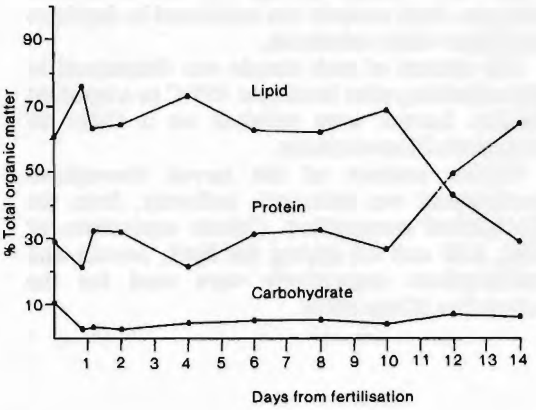

Fig. 2. Relative changes in lipid, protein and carbohydrate levels during larval development of *Hippopus hippopus*.

On settlement (day 10), lipid levels show a sharp decline from 226.39 μg/mg AFDW to 44.77 μg/mg AFDW on day 14. Relative changes in the levels of each biochemical fraction during larval development, and particularly on settlement are probably better understood when each fraction is expressed as a percentage of the total organic matter (Fig. 2). The percentage of each fraction remains relatively constant during development. The constantly low levels of carbohydrate result in any fluctuation in the percentage of lipid being mirrored by an opposite fluctuation in protein levels. From day 10 to 14, significant changes are evident in the percentages of a protein and lipid. Lipid levels decrease from 69.05% on day 10 to 29.16% on day 14, indicating that lipid is the major energy source for settlement. There is a corresponding rise in protein levels from 26.38% on day 10 to 64.58% on day 14.

Effect Of Short-Term Starvation

Short-term starvation resulted both in changes in the rate of shell growth and dry weight of the larvae. Larvae starved from day 3 to day 6 showed little difference in shell dimensions when compared to normally fed larvae, although dry weight (μg/larvae) and total organic matter (μg/mg AFDW) were considerably lower than in normally fed larvae. Starvation of older larvae (day 6 to 9) resulted in greater shell growth than normally fed larvae,

although dry weight (μg/larvae) decreased from 0.90 to 0.82 during the starvation period.

Biochemically, both periods of starvation resulted in lipid accounting for the main loss of organic matter, with losses of 49.05 μg/mg AFDW between days 3 to 6 and 19.93 μg/mg AFDW from day 6 to day 9. Protein levels also decreased between day 3 and day 6, to a lesser extent than lipid, losing 19.43 μg/mg AFDW. During day 6 to day 9, protein levels increased by 13.11 μg/mg AFDW. Carbohydrate levels changed little over both periods of starvation (Fig. 3).

Energetics

Changes in the energy content during larval development and settlement are shown in Fig. 4.

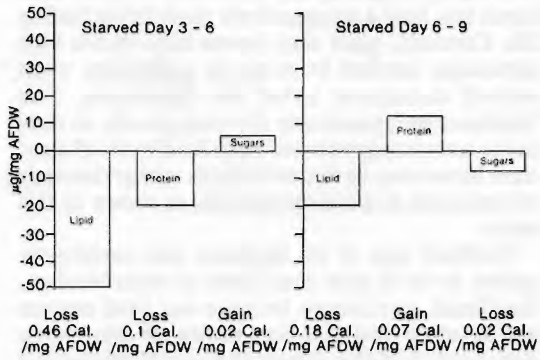

Fig. 3. Changes in the biochemical composition of *Hippopus hippopus* larvae during periods of enforced starvation.

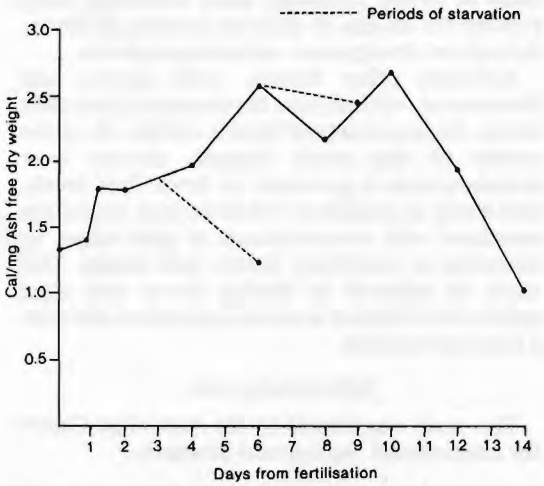

Fig. 4. Changes in the energy content of *Hippopus hippopus* larvae during development.

Caloric content (cal/mg AFDW) increased from 1.33 to 2.68 from fertilised egg to day 10 larvae, but then declined steadily during settlement to 1.02 on day 14. During periods of starvation lipid accounted for the main caloric losses through larval development. Lipid losses accounted for 0.46 cal/mg AFDW when 3-day-old larvae were starved for 3 days, and 0.18 cal/mg AFDW when larvae were unfed between day 6 and day 9.

Discussion

The results of this study have shown lipid to be the principal energy reserve of *Hippopus hippopus* larvae, and the major energy source for settlement and metamorphosis. A similarly important role for lipid has been shown for larvae of *Ostrea edulis* (Holland and Spencer 1973).

In contrast, protein rather than lipid has been shown to be the major energy reserve in a number of other bivalve larvae, including *Teredo navalis* and *Bankia gouldi* (Mann and Gallager 1985), *Martesia cuneiformis* (Mann and Gallager 1984), and *Crassostrea gigas* (Bartlett 1979).

The changes in the biochemical composition, and decrease in tissue energy content associated with settlement and metamorphosis, strongly indicate that *H. hippopus* is unable to feed during this period. Similar studies on *Ostrea edulis* have also indicated a similar inability to feed at this stage (Holland and Spencer 1973). The high level of lipid maintained during larval development declines sharply at settlement and the onset of metamorphosis. This decrease indicates that lipid is the major energy source for metamorphosis and, as such, it is likely that success at metamorphosis may be closely correlated with tissue lipid levels at the end of the larval feeding period. A close relationship between larval lipid levels and success at metamorphosis has been suggested for other bivalves (Holland and Spencer 1973; Holland 1978). Mann and Gallager (1985) have also suggested that for larvae of *Mercenaria mercenaria* to complete metamorphosis successfully, a minimum threshold tissue lipid level must be present.

Although phospholipids are utilised for energy in bivalve larvae (Bayne et al. 1975; Holland and Spencer 1973), the neutral lipid fraction has been shown to be more important as an energy source in times of nutritive stress and metamorphosis (Holland and Spencer 1973; Gabbott and Holland 1973; Gallager et al. 1986). It is likely that a similar pattern is true for *H. hippopus* larvae.

Protein levels rise steadily at settlement (day 10–14) when expressed as a percentage of the total organic matter. However, when expressed in terms of μg/mg AFDW, although rising between days 10 and 12, protein levels decrease between days 12 and

14. This may indicate that protein is utilised during settlement and metamorphosis, and not simply reorganised. Holland and Spencer (1973) reported no loss of protein on metamorphosis of *Ostrea edulis* larvae. Although lipid is the major energy reserve throughout larval development, protein is also utilised during starvation of early (day 3–6) larvae. Protein catabolism provided approximately 20% of the calories lost by unfed larvae between days 3 and 6. Protein utilisation as a secondary energy source during starvation has been shown for other bivalve larvae (Holland and Spencer 1973; Millar and Scott 1967), while in others protein is the major energy reserve (Bartlett 1979; Mann and Gallager 1984, 1985). Of interest is the increase in protein content in larvae starved between day 6 and 9. Increase in protein levels at the expense of lipid is a characteristic shown to be associated with settlement (day 10). This may indicate that starvation of older larvae stimulates premature settlement and the associated metabolic activity, in preference to the maintenance of normal metabolism which draws heavily on lipid reserves.

Carbohydrate remains at a low level and relatively constant through larval development, although increasing slightly at settlement. This indicates a very minor role for polysaccharides as a larval energy reserve, in contrast to adult bivalves where glycogen is the major reserve (Giese 1969). Changes in carbohydrate levels during starvation were small and likely to reflect changes in levels of free reducing sugars rather than polysaccharide.

The very high lipid content of the fertilised eggs was maintained throughout larval development. The high lipid levels contrast with the levels found in all other bivalve larvae so far studied. For example, lipid forms between 15.82% and 23.9% of the total organic matter in the eggs of five species of bivalves for which data are given in the review of Holland (1978). In contrast, egg protein content ranges from 70.5% and 81.6% for the same species.

In *H. hippopus* eggs approximately 60% of the total organic matter is composed of lipid, and a level above 60% is maintained throughout larval development. In other bivalve larvae, lipid levels are significantly lower. Lipid forms 16.66% of the total organic matter in *Mytilus edulis* (Bayne et al. 1975) and 11.7% in *Ostrea edulis* larvae (Holland 1978). During larval development of *O. edulis* lipid forms between 18.35% and 30.93% of the total organic matter, while protein makes up between 61.65% and 72.76% of the total (Holland and Spencer 1973). The results of this study vary greatly from similar published data for other bivalve eggs and larvae. In *H. hippopus*, high lipid levels result in comparatively low protein levels. Lipid staining techniques have shown *H.hippopus* larvae to possess a large number of lipid droplets dispersed throughout their tissue, particularly associated with the velum (Southgate unpublished data.) Although it is not unusual for bivalve larvae to possess lipid droplets, they are normally associated with early larval growth and in *Ostrea edulis*, *Mercenaria mercenaria* and *Crassostrea virginica* are resorbed within 4 days of the initiation of feeding (Gallager et al. 1986).

In *H. hippopus*, large numbers of droplets are visible in larvae which are 10 days old, just prior to settlement. High lipid levels in the larvae of *H. hippopus* may be a requirement for development in relatively nutrient-poor tropical waters where larval development may be limited by food availability. This aspect is particularly important in giant clam larvae that have a comparatively short larval feeding life. Certainly, giant clam larvae have shown high percentage survival from egg to pediveliger when starved throughout larval life (Southgate, This Monograph), presumably drawing heavily on lipid as the main energy reserve. High lipid levels of giant clam larvae may be due to the high energy demands of settlement and metamorphosis, as shown by this study.

Fertilised eggs of *H. hippopus* also contain far greater levels of lipid than those of other bivalves. Significant correlations between egg lipid content and larval survival have been shown for *Mercenaria mercenaria* and *Crassostrea virginica* (Gallager and Mann 1986). Helm et al. (1973) have also suggested that success of newly released larvae of *Ostrea edulis* was correlated with neutral lipid content. Parentally derived lipid levels in giant clam eggs may be very important in determining the success of a given batch of larvae. Certainly, great variability exists between the success of different batches of larvae, throughout development and metamorphosis.

Although other factors, both genetic and biochemical, will influence the success of giant clam larvae, the importance of lipid is evident. If, as the results of this study suggest, success over metamorphosis is governed by larval lipid levels, then it may be possible to reduce the high mortalities associated with metamorphosis of giant clams by increasing or modifying dietary lipid intake. This might be achieved by feeding larvae with algal species rich in lipid or a microencapsulated diet with a high lipid content.

Acknowledgments

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Photoadaptation in Juvenile *Tridacna gigas*

S. Suzanne M. Mingoa*

Abstract

Photoadaptation was demonstrated in the algal symbiosis of juveniles of the giant clam *Tridacna gigas*. Juveniles that were grown in unshaded ambient light required higher light intensities (about 200 $\mu E/m^2/sec$, 95% confidence interval: 194–218 $\mu E/m^2/sec$), for saturation of oxygen production, while those that were reared in approximately 90% shaded ambient light reached saturation at lower light intensities (150 $\mu E/m^2/sec$, 95% confidence interval: 126–175 $\mu E/m^2/sec$). Shade-reared clams had a higher chlorophyll *a* concentration per cell, and based on chlorophyll *a* had lower alpha, or photosynthetic, rates at subsaturating irradiance, and lower P_m, or maximum photosynthetic rates, at saturating irradiance.

P:R, specifically the ratio of net zooxanthellae photosynthesis to total respiration over 24 hours, of unshaded clams was significantly higher ($P < 0.05$) than values for shaded clams. All P:R ratios were higher than 1.0 indicating net primary production. CZAR values, the contribution of photosynthetically fixed carbon to host respiration, were higher in unshaded clams. Greater P:R and CZAR may account for the higher condition index (wet flesh weight/shell length) in unshaded clams.

Kept in darkness, juvenile clams lost condition within a few days and showed heavy mortality after 6 days. This may support the P:R results in showing the dependence of juvenile clams on their algal symbionts for a major part of their nutrition.

THE dependence of tridacnid bivalves upon the photosynthetic activities of endosymbiotic zooxanthellae living within their hypertrophied mantle restricts the distribution of this group of bivalves to sunlit waters (Jaubert 1977). According to Trench et al. (1981), photosynthetically fixed carbon is translocated to the animal, which relies on algal symbionts for at least 50% of metabolic carbon requirements.

Incident light at the water surface is modified as it penetrates seawater (Jerlov 1976), such that zooxanthellae photoadapt using various mechanisms, for example, by increasing the size of the photosynthetic unit (PSU), i.e. by increasing light-capturing chlorophyll *a* pigments (Chang et al. 1983). Such a change may affect the ratio of zooxanthellae photosynthesis to animal respiration, and hence the amount of carbon available for translocation. Photoadaptation has been demonstrated in *Tridacna gigas* in relation to animal size (Fisher et al. 1985) and in hermatypic reef corals (Wethey and Porter 1976a, b; Dustan 1979, 1982; Titlyanov et al. 1980; Zvalinskii et al. 1980; Falkowski and Dubinsky 1981). Little is known about photoadaptation in tridacnid juveniles.

The aims of this study were to determine (1) the survival of *T. gigas* juveniles and their condition in the absence of light; (2) whether photoadaptation occurs in different light regimes; and (3) changes in the chlorophyll *a* concentration of zooxanthellae in vivo under low and high light intensities.

Materials and Methods

Survival and Animal Condition

These experiments were conducted at Orpheus Island Research Station. Eleven-month-old *T. gigas*

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with shell lengths between 15 and 20 mm were randomly grouped into 5 batches of 20 clams. Four groups ('dark' clams) were each placed in 10-l aquaria which were covered with black plastic to totally exclude light. The remaining group, serving as a control, was placed in a 10-l aquarium with access to natural daylight. All aquaria had constantly flowing seawater. Dead clams from one batch of 'dark' clams were counted every 3 days to determine the rate of survival.

To determine flesh weight and shell length, clams from the same group were placed in the dark and in the light, 30 animals each per 10-l aquarium. Initial shell lengths were measured with a vernier caliper (±0.02 mm) and corresponding dry tissue weights (± .01 mg) determined from a representative batch. Each day for 6 days, one batch of 'dark' clams was dissected and the soft tissue dried at 65°C. The control was dissected with the last batch of 'dark' clams. Animal condition was expressed as the rate of dry tissue weight/shell length.

Acclimation to Light Intensities

Eight-month-old juveniles with shell lengths of 11.78 ± 2.09 mm (mean ± SD) were acclimated to low and high light environments for 53 days. They were placed in ambient light with 45 clams in 90% shade and the same number in direct light. Changes in irradiance over 12 hours of light were determined for both unshaded and 90%-shaded light treatments on a clear day with a Li-Cor quantum photometer and a submersible quantum sensor. Both treatments were maintained in running 1-μm filtered seawater (FSW) with adequate aeration. The growth of filamentous algae along with the clams necessitated periodic cleaning by siphoning. Due care was taken to ensure minimal disturbance to the clams.

Clam Photosynthesis and Respiration Rates

A 4-ml respiration chamber was used to measure oxygen production and consumption by the intact clam. A single clam lying on its side was placed on a platform in the chamber. The chamber was filled with 0.45 μm FSW and sealed with a rubber bung which held the glass oxygen electrode (Radiometer E5046-0) in place through a central bore. A stirrer bar maintained constant water circulation around the electrode. The chamber was submerged in a water bath (MGW Lauda RC6) at 27.8 ± 0.1°C. The numbers of clams used from shade and unshaded treatment were 4 and 5, respectively.

Illumination was provided by a light projector bulb (Elmo Projector Lens, F:2.8, f = 85 mm). Irradiance levels ranging from 10 to 700 $\mu E/m^2/sec$ were obtained by moving the light source away from or towards the chamber. Irradiance was measured at the chamber surface by a Li-Cor quantum photometer and a nonsubmersible quantum sensor. Respiration rates were measured in the dark by covering the chamber with black plastic.

Oxygen flux was measured with the oxygen electrode connected to a Radiometer PHM72 Mk2 Digital Acid-Base Analyzer. Continuous recordings were obtained using an REC80 Servograph with a REA 112 High-sensitivity Unit. Irradiance was altered at random to avoid any conditioned response. All measurements were conducted between 10 a.m. and 7 p.m.

The rates of oxygen production and consumption by juveniles previously subjected to low and high light regimes were measured after epiphytes adhering to the shell were removed. Rates of oxygen production (net photosynthesis) and consumption (respiration) were expressed in terms of wet flesh weight and chlorophyll *a* (Forstner 1983).

Isolation of Zooxanthellae

At the conclusion of oxygen flux measurement, the flesh was removed from the shell, blotted briefly and weighed. The inner mantle fold was excised and cut up finely on a glass slide. Zooxanthellae were extracted from the mantle by maceration using a Teflon tube homogeniser. The homogenate was filtered through three layers of cheesecloth to remove animal tissue debris and obtain a yellow-brown filtrate containing zooxanthellae. The filtrate was centrifuged repeatedly at about 1000 rpm until the supernatant was clear, discarding the supernatant and resuspending the pellet with FSW.

Numbers of zooxanthellae were determined under the microscope with a Petroff-Hausser counting chamber. Preliminary observations showed that clams 20 mm or smaller have fewer than 10^6 algal cells per clam.

Zooxanthellae Photosynthesis and Respiration Rates

Photosynthesis and respiration rates of isolated zooxanthellae were determined in the same manner as for the intact clam. Since an individual of the size used did not have enough zooxanthellae to meet the required experimental density (10^6/ml) for measurement, zooxanthellae were isolated from the clams after oxygen flux determination and pooled for each treatment. No attempt was made to determine the number of zooxanthellae for each clam. With the small sample available, cells could not be replaced after being measured at a certain irradiance. Rates of net photosynthesis and respiration were expressed in terms of chlorophyll *a*.

Quantitation of Chlorophyll *a*

The zooxanthellae sample (10^6 cells/ml) was centrifuged at 3000 rpm for 2 min to sediment the

cells. The pellet was resuspended in 3 ml of 100% acetone with a drop of magnesium carbonate added to prevent pigment degradation (Prezelin 1976). The sample was covered with Parafilm and kept in the dark at 0°C overnight for pigment extraction. The chlorophyll extract was centrifuged at 3000 rpm for 2 min. Absorbance of the supernatant was measured at 630 and 663 nm with a Hitachi U-3200 spectrophotometer, and the amount of chlorophyll *a* determined using the equation of Jeffrey and Humphrey (1975).

Data Analysis

The rate of oxygen flux was expressed as the rate of gross photosynthesis which is the sum of the rates of net photosynthesis and respiration. Gross photosynthesis was plotted against light intensity, and the curve estimated by the hyperbolic tangent function (Chalker 1980):

$$P = P_m \tanh (I/Ik)$$

where P is the rate of gross photosynthesis at a specific irradiance (I), P_m is the rate of gross photosynthesis at the level of saturating irradiance, and Ik is the irradiance at which alpha, the initial slope of the curve, intersects P_m. The statistical program used was BMDP3R (Health Sciences Computing Facility, University of California, Los Angeles, California, 90024, USA). Alpha was computed using derived estimates:

$$\text{alpha} = P_m/Ik.$$

Results

Survival and Animal Condition

The juvenile clams maintained in the dark showed heavy mortality after 6 days in contrast to 100% survival of juveniles exposed to light. Percentage survival was 95% on the 6th day, 35% on the 9th day, and 5% on the 12th day for clams kept in the dark. Condition indices (CI) decreased through time in the absence of light from an initial mean CI of 0.62 mg/mm ± 0.102. The mean CI of clams exposed to light was 0.637 ± 0.083 mg/mm. Clams maintained in the dark had an average CI of 0.541 ± 0.084 mg/mm, indicating that they were starving, which accounts for the mortality in darkness.

There was no significant difference in shell lengths between the initial samples, clams kept in the dark and those kept in the light (ANOVA, $P > 0.05$). The average shell length from pooled data was 17.52 mm (SD = 1.0).

Photosynthesis-Irradiance Curves

Variations in light intensity on a clear day for a period of 12 hours for treatments of no-shade and under-90% shade screen were measured. In unshaded conditions, clams may receive as much as 2500 $\mu E/m^2/sec$, whereas, in 90% shaded conditions, only about 250 $\mu E/m^2/sec$.

Rates of gross photosynthesis at different light intensities for clams acclimated to low and high light regimes are shown in Fig. 1. For convenience, 'shade' clams refers to clams exposed to low light intensities while 'light' clams refer to clams exposed to high light intensities. The curves show the characteristic shape of light-saturation curves, i.e. a gradual increase in oxygen production with increasing irradiance within subsaturating levels, then rapidly approaching an asymptote.

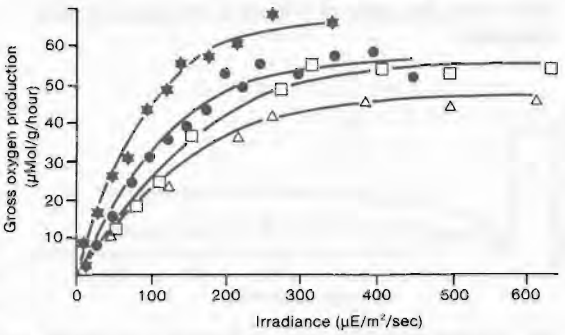

Fig. 1. Gross production rates of intact juvenile clams, based on wet flesh weight, at different light intensities. Closed symbols = clams from 90% shade, open symbols = clams from unshaded ambient light. Pairs of curves show the range of P-I curves obtained for each treatment.

On a wet flesh weight basis, alpha and P_m values of 'shade' clams were higher than those obtained for 'light' clams, indicating higher gross oxygen production by the former at subsaturating and saturating irradiance levels. These values were converted based on chlorophyll *a*, which was 0.38 µg for 'light' clams and 1.03 µg for 'shade' clams, resulting in a reversal of trends (Fig. 2): the values of alpha and P_m of 'shade' clams were lower than those of 'light' clams, thus indicating a lower gross oxygen production at subsaturating and saturating light intensities by 'shade' clams. A simple *t*-test ($P < 0.05$) on wet flesh weight:shell length indices of the 'shade' and 'light' clams shows that the wet flesh weight of 'shade' clams was significantly lower than that for 'light' clams despite their similar sizes (*t*-test, $P > 0.05$). This difference in weight may reflect the higher alpha and high P_m (based on flesh weight) for 'shade' clams. However, it is also possible that the number of zooxanthellae per unit wet flesh weight may account for the results of alpha and P_m, but no data were obtained to support this.

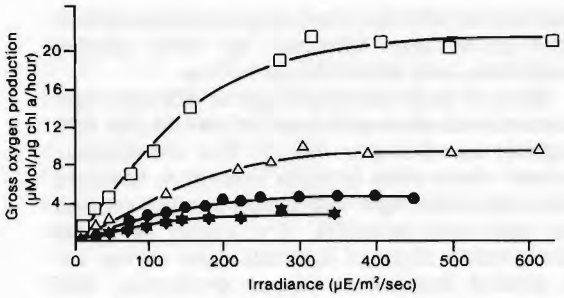

Fig. 2. Gross production rates of intact juvenile clams, based on chlorophyll *a* content, at different light intensities. Open symbols = clams from unshaded ambient light, closed symbols = clams from 90% shade. Pairs of curves show the range of P–I curves obtained for each treatment.

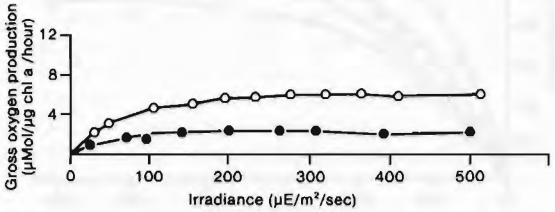

Fig. 3. Gross production rates of isolated zooxanthellae pooled from juvenile clams, based on chlorophyll *a* content, at different light intensities. Open circles = clams from ambient light, closed circles = clams from 90% shade.

Based on chlorophyll *a* content, alpha, P_m and Ik of 'shade' clams were significantly lower than those of 'light' clams. The rates of oxygen production of 'shade' clams at subsaturating irradiance were lower, with P_m at 170 $\mu E/m^2/sec$, whereas 'light' clams had P_m at 200 $\mu E/m^2/sec$.

P-I curves generated from pooled zooxanthellae isolated from similarly treated clams are shown in Fig. 3, with gross photosynthesis based on chlorophyll *a*. They have the same characteristic curve, showing similar general trends as for the 'shade' and 'light' clams. Alpha, P_m and Ik were lower for 'shade' zooxanthellae. Comparing the P-I curves of the intact clam association and their isolated zooxanthellae, the P_m values of the isolated zooxanthellae were lower than the lowest P_m value of the intact clam for both treatments. Also, isolated zooxanthellae yielded a maximum oxygen production at a much lower Ik about 80 $\mu E/m^2/sec$ compared to in vitro measurements. No generalisation can be made between the alpha values of isolated zooxanthellae and of intact clams.

Ratios of net zooxanthellae photosynthesis to animal respiration over 24 hours (P:R) and the

TABLE 1. Daily P:R and %CZAR in *T. gigas* juveniles adapted to high and low light intensities.

	P:R	%CZAR (T = 32%)
'Light' clam		
1	2.77	88.64
2	3.33	106.57
3	2.31	73.84
4	3.19	102.13
5	2.76	88.29
Mean	2.90	91.90
'Dark' clam		
1	2.66	85.05
2	2.41	77.13
3	2.13	68.22
4	1.91	61.19
Mean	2.30	72.90

Irradiance ($\mu E/m^2/sec$)

contribution of photosynthetically fixed carbon to host respiration (CZAR) were determined for each clam (Table 1), with the following assumptions: the period during which the clams were under saturating light intensity corresponds to *t*day, the rates of daytime and nighttime respiration are equal, respiration rate assumes a 24-hour period, PQ equals 1.1, RQ equals 0.8 (Muscatine et al. 1981), and the total respiration rate is attributed to 5% algal respiration and 95% actual animal respiration (Trench et al. 1981). Calculated P:R values varied significantly ($P < 0.05$) with an average of 2.9 for 'light' clams and 2.3 for 'shade' clams. All values were higher than 1.0, indicating the potential of photosynthetically fixed carbon as a source for the host clam's carbon requirements.

CZAR was determined assuming 32% translocation (Griffiths, D. unpublished data), using the equation (Muscatine et al. 1981):

$$\text{CZAR\%} = \frac{(P^\circ \times t\text{day})(0.375PQ^{-1}) - (1-\beta)(R_a^\circ \times 24)(0.375RQ)}{(\beta)(R_a^\circ \times 24)(0.375RQ)} \times T\%$$

where P° is gross oxygen production at saturating light intensity, R_a° is the average respiration rate of the intact clam, $(1-\beta)$ is the algal contribution to total respiration, and β is the animal contribution to total respiration. CZAR values varied significantly ($P < 0.05$) with an average of 91.9% for 'light' clams and 72.9% for 'shade' clams. This means that under low light intensity, zooxanthellae produced and translocated less carbon products to the clam than they would under a high light regime.

Discussion

The importance of light to algal symbiotic relationships depends on the ability of the algae to

adapt to short- or long-term changes in their photic environment, and on the ability of the animal to oscillate between autotrophy and heterotrophy. This is illustrated by several studies on reef corals. For example, *Stylophora pistillata* is found in light-exposed habitats, as well as in caves. For light-adapted *S. pistillata*, the contribution of zooxanthellae-fixed carbon to animal respiration (CZAR) is 143%, in contrast to the CZAR of 58% in shade-adapted corals which, therefore, must acquire some portion of their respiratory carbon demand by heterotrophic feeding (Muscatine et al. 1984). Another hermatypic coral *Acropora* can maintain a constant photosynthetic rate between 1 and 35 m where surface light transmittance decreases from 85% to 5.8% (Chalker and Dunlap 1984).

Light attenuation also occurs within animal tissue. In tridacnid clams, the thickness of the expanded mantle housing zooxanthellae in dense numbers increases with increasing animal size. Shading by zooxanthellae in vivo reaches a maximum of 97% in 24-cm *T. gigas* compared to 34% for 1-cm clams (Fisher et al. 1985).

Translocated carbon is significant to alga-invertebrate symbioses that cannot meet their daily carbon requirements from external food sources (Porter 1974). In our work, the exclusion of light from *T. gigas* juveniles precluded the fixing of carbon by photosynthesis, and hence the absence of any translocation. The decrease in the condition index (wet flesh weight/shell length) indicated that the animal could not obtain sufficient energy from other food sources to maintain its basal metabolic processes. The relative contribution of other sources of nutrition (plankton, particulate matter, dissolved organic and inorganic nutrients) in *T. gigas* juveniles has not been quantified.

Mechanisms of photoadaptation in zooxanthellae of different host species have been studied in vivo (e.g. Wethey and Porter 1976a, b; Dustan 1979, 1982) and in vitro (Chang et al. 1983). Some of these mechanisms involve changing the PSU size, the PSU number, or the activities of the electron transport system (Chang et al. 1983). Morphological adaptations have been recorded for shade species, for instance, increasing the number of polyps per unit area in some corals (Zvalinksii et al. 1980). In the present study, zooxanthellae in *T. gigas* juveniles were able to adapt to low light intensities, the maximum light attainable on a clear day being 250 $\mu E/m^2/sec$, by increasing their chlorophyll *a* pigment concentration. Chlorophyll *a* concentration of zooxanthellae from shade-adapted juveniles was more than twice that of light-adapted clams. Consequent variations in the *P–I* curve parameters were lower alpha, P_m and Ik, similar to the results of Porter et al. (1984) for *S. pistillata*. Except for alpha, the trends were similar to those obtained from *T. maxima* zooxanthellae grown in culture at different light intensities (Chang et al. 1983). Porter et al. (1984) suggested that lower alpha values for shade-adapted species may be due to the lower efficiency of their chlorophyll *a* molecules in harvesting incident light (Dubinsky et al. 1984). This is applicable to species that adjust their chlorophyll *a* concentration per cell under low irradiance conditions. The disparity between the photosynthetic response of *T. maxima* and *T. gigas* zooxanthellae may be caused by differences between zooxanthellae strains, other photoadaptive mechanisms not yet identified (Chang et al. 1983), or unknown factors in the host which depress the light-harvesting capacity of chlorophyll *a* molecules in subsaturating irradiance.

Freshly isolated zooxanthellae from *T. gigas* reached oxygen saturation at lower light intensities than when in vivo. The same phenomenon was reported by Fisher et al. (1985), who enumerated the following possible causes: (a) physical damage to zooxanthellae during the isolation procedure resulting in partial inhibition of photosynthesis; (b) zooxanthellae may produce superoxide anions giving rise to hydrogen peroxide which cannot be detected by the oxygen electrode (Dykens and Shick 1982); and (c) other 'factors' in the host which could enhance photosynthesis in zooxanthellae (Deane and O'Brien 1980).

The effect of decreased CZAR was manifested in the condition index of shade-adapted *T. gigas* juveniles. In comparison to light-adapted clams, algal photosynthesis was less efficient, such that, even as the P:R ratios of shade-adapted clams exceeded 1.0, less carbon was fixed and made available to the host.

Studies have shown that the extent and nature of photoadaptation varies with different zooxanthellae from different host species and may be related to their ecological distribution. Chang et al. (1983) found that *T. maxima*, living where incident irradiance reaches extremely high levels, had the least photoadaptive capability, compared to the sea anemone *Aiptasia pulchella* which inhabits both shaded and sunlit environments, and the reef coral *Montastrea verrucosa* which thrives better in low irradiance conditions. By the same token, the varied habitats occupied by tridacnid species may also be characterised by different photic conditions, possibly influencing their photoadaptability. This still requires investigation.

The implications of the present study are relevant to mariculture, in terms of selection of light regimes for optimum growth of giant clams. For example, in pilot studies of tridacnid juvenile rearing in shore-based tanks, shade screens were used to control filamentous algae overgrowing the small juvenile

clams. The present study illustrated the effects of heavy shading on the physiology of *T. gigas*.

Acknowledgments

The author thanks Drs J. Baker and D.J. Barnes, Australian Institute of Marine Science (AIMS), for the use of laboratory and computer facilities; Dr B.E. Chalker (AIMS) for assistance with the computer program; Prof D. Griffiths and Prof J.S. Lucas, James Cook University, and Drs D.J. Barnes and B.E. Chalker for helpful criticisms of this paper; Mr M. Devereux and Ms J. Wu Won (AIMS) for assistance with equipment. This study was funded by an AIDAB–ACIAR grant.

Contribution of Zooxanthellae to Their Giant Clam Host

D.J. Griffiths and M. Streamer*

Abstract

Zooxanthellae (*Symbiodinium microadriaticum*) symbiotic with juvenile clams of *Tridacna gigas* transfer approximately 30% of photosynthetically fixed carbon to their host during a 10-min incubation period. The major early products of ^{14}C-photosynthesis (glucose, oligosaccharides, glutamate, alanine, aspartate, serine, succinate) and their relative amounts, were similar for in situ and isolated zooxanthellae and were also detected in host tissues following short-term incubations (1–10 min) of whole clams. Evidence from the time-course of labelling of early products of photosynthesis and from pulse-chase incubations suggests that glucose is the major product transferred from zooxanthellae to host. It accounts for over 40% of the total labelling in host tissue after 1 min of ^{14}C-photosynthesis and later declines in importance with increased labelling in other compounds. Glycerol occurred in significant quantities only as an extracellular product of photosynthesis by isolated zooxanthellae incubated in the presence of host tissue extracts.

THE algal symbionts of giant clams are located in the haemal sinuses of the mantle which is greatly expanded to allow maximum exposure to light. It might be expected, therefore, that there would be a well-developed mechanism by which some of the free energy of algal photosynthesis could be made available to the host.

This transfer of energy could occur either through the algae (the zooxanthellae) being 'farmed' by amoebocytes in the haemal fluid and subsequently digested by lysosomal activity, or through excretion of metabolites by the algae into the haemal fluid and subsequent incorporation of this material into host cells and tissues.

Of these two alternatives the latter seems to be by far the more likely since there are many reports (e.g. Trench et al. 1981) of living zooxanthellae in the faeces of *Tridacna* suggesting that the algae are protected from digestion during passage through the clam's digestive tract.

Evidence for direct transfer of metabolites from zooxanthellae to their clam host is surprisingly sparse and much of it is indirect since it is based largely on experiments with isolated zooxanthellae. Thus, in his studies with *T. crocea* Muscatine (1967) showed that isolated zooxanthellae suspended in a seawater medium excreted no more than 2% of their total photosynthetically fixed carbon. However, when they were supplied with an aqueous extract from homogenised host tissue, they excreted up to 40% of their photosynthetically fixed carbon. Similarly, Trench et al. (1981) estimated that isolated zooxanthellae from *T. maxima* incubated in the light in the presence of host tissue homogenate excreted between 39 and 45% of their photosynthetically fixed carbon.

Data from such experiments have often been extrapolated to the in vivo situation and used to calculate the contribution of photosynthetically fixed carbon to the respiratory carbon requirement of the host. Moreover, analyses of the major products excreted by isolated zooxanthellae have often been cited as evidence of the nature of the metabolites transferred from zooxanthellae to host in the intact association.

But such extrapolations assume that isolated zooxanthellae photosynthesising in vitro behave in the same way as in situ zooxanthellae in their

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protected and very specialised environment within the host mantle tissue. Since we really have no evidence that this is so, conclusions drawn from such indirect evidence must be accepted with caution. We therefore need a more direct assessment of what actually happens in the intact association with both partners functioning under conditions approximating those experienced in nature.

Attempts to obtain direct evidence from intact clam–zooxanthellae association have been made — for example by Goreau et al. (1973) who used autoradiographic techniques to trace the pathway of ^{14}C-labelled photosynthetic products from the algae into the tissues of the host giant clam (*T. maxima* f. *elongata*). The results obtained by this technique are inevitably qualitative since preparation of the tissues for histological examination involves loss of some water-soluble compounds and most of the fat-soluble compounds. But clear evidence was obtained of the incorporation of ^{14}C-labelled photosynthetic products into host tissue — most notably into those glands concerned with the normal mode of feeding and digestion in bivalves.

There is clearly a need therefore for an unequivocal demonstration of the nature and amounts of the photosynthetic products that are transferred from zooxanthellae to host in the intact clam association. We have attempted to do this for juvenile clams of *Tridacna gigas*.

Materials and Methods

Juvenile clams of *Tridacna gigas* (25–30 mm shell length) were supplied with $NaH^{14}CO_3$ (37×10^4 Bq/ml) in the light (500 $\mu E/m^2/sec$). Sample clams (3–5/sample) were removed at intervals, the zooxanthellae separated from the host tissue by homogenisation, filtration through two layers of cheesecloth and centrifugation ($2.3 \times 10^3 g$). The pelleted zooxanthellae were washed ($\times 3$), digested with 20% $HClO_4$ at 100°C for 4 min, neutralised with K_2CO_3 and the precipitate removed. The supernatant host tissue was freeze-dried, extracted ($\times 3$) with ethanol, evaporated to dryness and the residue dissolved in water. The zooxanthellae and host fractions were then subjected to analysis by Standard High Performance Liquid Chromatography. Monosaccharides, oligosaccharides, organic acids and amino acids were separated and their identity confirmed against authentic ^{14}C-labelled standards.

Radioactivity in various extracts and in the identified early products of photosynthetic $^{14}CO_2$ fixation was determined by liquid scintillation spectrometry and normalised on a chlorophyll *a* basis determined from acetone extracts (Jeffrey and Humphrey 1975).

Results and Discussion

Figure 1a shows that the incorporation of radioactivity from supplied $^{14}CO_2$ into intact juvenile clams was almost linear over a 10-min period. Looking at the two components of the association separately (Fig. 1b) it can be seen that most of the incorporated radioactivity is associated with the algal fraction with a smaller proportion (30% after 5 min, 32% after 10 min) being associated with host tissue.

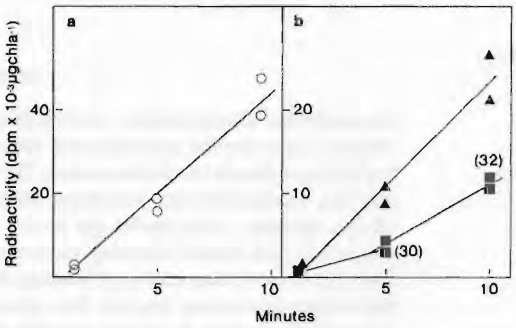

Fig. 1a. Light-dependent incorporation of radioactivity from supplied $^{14}CO_2$ into whole clams of *Tridacna gigas*. **Fig. 1b.** Light-dependent incorporation of radioactivity from supplied $^{14}CO_2$ into the host (■) and zooxanthellae (▲) fraction of the *Tridacna gigas* association. Figures in parentheses show mean values for radioactivity associated with host tissue as a percentage of the total fixed. Both figures show the results of duplicate experiments (25°C, 500 $\mu E/m^2/sec$).

Since, to effect removal of the algae from the host tissue, all the soft parts of the clam were macerated after the incubation period, it is not possible to say whether radioactivity within the host was associated with mantle tissue only or was more widely distributed to other tissues and organs.

The results of a pulse-chase experiment in which whole clams were exposed to $^{14}CO_2$ in the light for 1 min, then washed in filtered seawater and finally reincubated in the light (or in the dark or in light + 3-(3,4-dichlorophenyl)-1,1-dimethyl urea(DCMU)) with unlabelled CO_2 for a further 5 min, showed that radioactivity in the zooxanthellae continues to increase during the chase period in the light — presumably due to continued incorporation of $^{14}CO_2$ from ^{14}C-bicarbonate not removed by washing at the end of the pulse period. But there was a greatly reduced transfer of radioactivity to the host during the chase period. Even in the absence of photosynthesis (dark or light + DCMU) there was no significant drop in radioactivity remaining in the zooxanthellae, suggesting that transfer of metabolites from algae to host is strongly linked with photosynthesis.

The early products of photosynthesis by isolated zooxanthellae are shown in Fig. 2a. The major product is glucose, and the next most abundant is represented by a group of oligosaccharides having glucose as the major product of acid hydrolysis. Approximately 45% of the radioactivity associated with these oligosaccharides could be assigned to disaccharides, 19% to trisaccharides. Other products were glutamate, aspartate, succinate, alanine and glycerol in that order of abundance.

For in situ zooxanthellae, that is, those photosynthesising within the mantle tissue of the juvenile clams, the same major products were identified, in roughly the same order of prominence except that no glycerol was detected (Fig. 2b).

Changes with time in the proportion of fixed radioactivity in the early products of photosynthesis (Fig. 2c and d) show major differences between isolated and in situ algae in the time-course of labelling. For in situ algae glucose maintained (over the 10-min period) a dominant position relative to the other photosynthetic products whilst in isolated zooxanthellae radioactivity in glucose declined (as a percentage of the total) with time, suggesting that it (and perhaps the oligosaccharides) is a precursor of some other compounds, not appearing in these extracts but accounting, according to our estimations, for approximately 20% of the total labelling after 10 min incubation.

This difference reflects some basic differences in the metabolic patterns of isolated and in situ zooxanthellae and points to the importance of glucose as a major end-product for in situ algae — perhaps as the major exported compound.

Glucose is certainly a major photosynthetic product to appear early in the host tissue as can be seen in Fig. 3a. It accounts for over 40% of the total labelling after 1 min of photosynthesis, but declines slightly in importance thereafter in favour of increased relative labelling in other compounds (Fig. 3b).

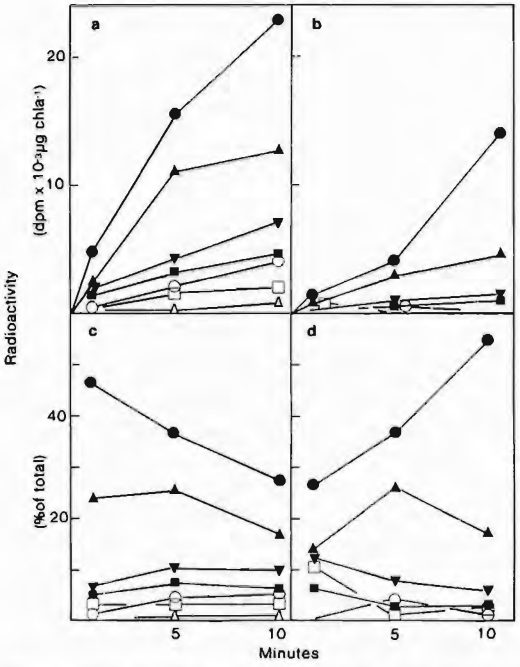

Fig. 2. Radioactivity in the early products of photosynthetic $^{14}CO_2$ fixation by isolated (a) and in situ (b) zooxanthellae of *Tridacna gigas*; and radioactivity in the products expressed as a percentage of the total fixed by isolated (c) and in situ (d) zooxanthellae (●-glucose, ▲-oligosaccharides, ▼-glutamate, ■-aspartate, ○-succinate, □-alanine, △-glycerol).

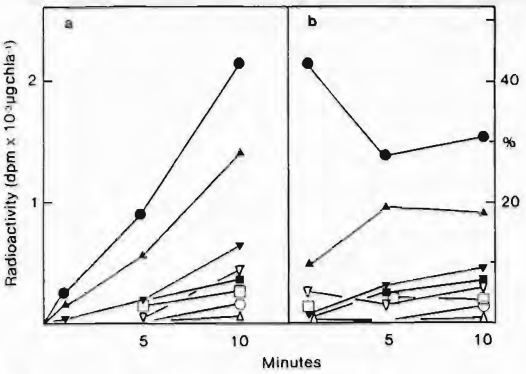

Fig. 3a. Radioactivity in the early products of photosynthetic $^{14}CO_2$ fixation accumulating in the host tissue of *Tridacna gigas*.

Fig. 3b. Percentage distribution of radioactivity in the early products of photosynthetic $^{14}CO_2$ fixation accumulating in the host tissue of *Tridacna gigas* (25°C, 500 $\mu E/m^2/sec$). (●-glucose, ▲-oligosaccharides, ▼-glutamate, ∇-unidentified monosaccharide, ■-aspartate, □-alanine, ○-succinate, △-serine).

It is interesting to note that glycerol, a compound previously reported by Muscatine (1967) to be the major excretory product of photosynthesis by isolated zooxanthellae, could not be detected in our host extracts. The initial high level of relative radioactivity in glucose and its subsequent decline during the incubation period (Fig. 3b) suggests that it is the more likely major product transferred.

Our failure to detect glycerol as a major photosynthetic product accumulating in host tissue following in situ incubations led us to repeat Muscatine's experiments with isolated zooxanthellae. We were then able to confirm that glycerol is indeed a major excretory product of photosynthesis by isolated zooxanthellae of *T.*

gigas, especially in the presence of host tissue extracts (when it accounted for up to 33% of the total excreted material compared with 8% in the absence of host tissue homogenate). We are forced to conclude, therefore, that the appearance of glycerol in the outside medium under in vitro incubation in the presence of host tissue extracts may be due to uncontrolled metabolic processes in the crude extract.

Thus is appears that in *T. gigas* at any rate, glycerol does not figure as prominently in translocation as it undoubtedly does in other algal-invertebrate symbiotic associations. This particular role in *T. gigas* is apparently assumed by glucose and the oligosaccharides with glycerol either turning over very rapidly or playing an altogether more minor role.

It may be significant that the autoradiographic studies of Goreau et al. (1973) showed that ^{14}C-labelled photosynthetic products accumulate primarily in glands associated with mucus production (that is, the pallial and ctenidial glands) and that Trench (unpublished but reported in Goreau et al. 1973) has reported that algal photosynthetic products become chemically incorporated into the style of *T. crocea* as polysaccharide-protein complexes. It would appear therefore that in the tridacnids generally photosynthetically fixed carbon becomes incorporated primarily into muco-polysaccharides for which, according to our results with *T. gigas*, glucose or a glucose-containing oligosaccharide is the major precursor.

Acknowledgments

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Use of Microencapsulated Diets in the Culture of Giant Clam Larvae

Paul C. Southgate*

Abstract

The digestion of microcapsules and assimilation of encapsulated nutrients by giant clam larvae were investigated. Larvae readily ingested the four types of microcapsules used in this study. Ingested microcapsules took up to 72 hours to be completely digested. Radioactivity from microencapsulated ^{14}C-labelled carbohydrate and lipid was incorporated into larval tissues, demonstrating digestion of microcapsules and the assimilation of encapsulated nutrients.

In a growth trial using a simple microencapsulated diet, 1.68% of larvae fed the artificial diet survived to 1 month post metamorphosis, compared to a survival of 1.7% for larvae fed *Isochrysis galbana*. Larvae that were starved throughout development did not survive beyond metamorphosis.

The implications of the results of this study, and the potential for use of microcapsules in giant clam hatcheries, are discussed.

A major problem associated with hatchery culture of bivalves is the provision of a larval feed of consistent quality. Traditionally, bivalve hatcheries have relied on live larval feeds in the form of microalgae, which are costly, difficult to culture, labour-intensive, and are often inconsistent in their nutritional composition. Microencapsulation provides a means whereby larval diets can be engineered to have the correct nutritional composition of consistent quality. Depending on the type of microcapsule, dietary nutrients are either separated from the culture water by an insoluble but digestible membrane, or bound in a gelled matrix, thereby greatly reducing or eliminating nutrient leaching and the associated bacterial problems. Microencapsulated diets can be dried and stored in a dry state without affecting their nutritional value, and as such represent an ideal 'off-the-shelf' diet.

This paper reports on the acceptability and digestibility of various types of microcapsules by giant clam larvae, and presents preliminary results of growth trials, using a simple microencapsulated diet.

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Materials and Methods

Of the many types of microcapsules initially investigated for their suitability in presenting dietary nutrients to giant clam larvae, four types seemed to have the greatest potential (Fig. 1).

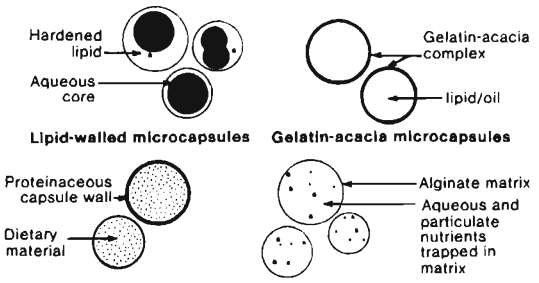

Fig. 1. Types of microcapsules used in the study.

Gelatin-Acacia Microcapsules

Gelatin-acacia microcapsules containing cod liver oil were manufactured based on the method of

Green and Schleicher (1957). These microcapsules have a wall composed of a gelatin-acacia complex encapsulating a core material. This method can only be used to encapsulate water-insoluble materials such as fats and oils and insoluble particulate matter. The major disadvantage of this type is that water-soluble nutrients, and therefore complete diets, cannot be encapsulated.

Lipid-Walled Microcapsules

Lipid-walled microcapsules were prepared by a method modified from Langdon and Siegfried (1984). This microcapsule consists of an aqueous core encapsulated within a wall of solidified lipid. Both aqueous nutrients and lipids can be encapsulated within the same microcapsule.

Protein-Walled Microcapsules

The microcapsules were manufactured by a method based on that of Jones et al. (1976, 1979) as described by Teshima et al. (1982). The microcapsules are formed by a reaction with dietary protein to form the microcapsule wall.

Alginate Particles

Alginate particles, which consist of a gelled matrix through which dietary nutrients are dispersed and trapped, were manufactured by a method based on that of Langdon and Bolton (1984). The particle matrix may contain microdroplets and/or particles of dietary material and also bind solutions of aqueous nutrients.

Digestion Experiment

For digestion experiments, microcapsules containing coloured stains were manufactured. Staining of microcapsules allowed observation of capsules within the gut of giant clam larvae. Gelatin-acacia and lipid-walled microcapsules were made containing the lipid soluble stain Sudan III. Alginate particles were manufactured, containing a purple food dye. Four-day-old *Tridacna gigas* larvae, which had been unfed prior to the experiment, were placed in 100-ml glass beakers in 1.0-μm filtered seawater at a stocking density of approximately 5/ml. Each type of microcapsule was fed to the larvae at 20 000 capsules/ml for 9 hours. After this period, a sample of the larvae was taken and preserved. The remaining larvae were washed free of microcapsules and placed in clean 1-μm-filtered seawater. Further samples of the larvae were taken at 12, 24, 36, 48, 60 and 72 hours, after feeding was terminated. Larval samples were preserved and subsequently observed microscopically. The percentage of larvae in each sample with coloration to the gut, and the degree of coloration were recorded. When coloration was no longer visible throughout the gut, complete digestion of the ingested capsules was assumed to have taken place.

Assimilation of Microencapsulated Nutrients

Protein-walled microcapsules were manufactured containing two diets: (1) 35% v/v whole chicken egg yolk containing 50 μCi ^{14}C glucose (specific activity 4 mCi/mmol, Amersham); and (2) 3 parts 66% v/v whole chicken egg yolk plus 1 part cod liver oil containing 7 μCi ^{14}C cholesterol (specific activity 57 μCi/mmol, Amersham).

Gelatin-acacia microcapsules containing cod liver oil in which 12.5 μCi ^{14}C cholesterol had been dissolved were manufactured as previously described.

Four-day-old unfed *T. gigas* larvae were placed in 1-l beakers with 0.45-μm-filtered seawater, containing 50 mg/l streptomycin sulfate and 3 mg/l chloramphenicol, at a stocking density of 5 larvae/ml. Microcapsules were added at approximately 20 000/ml, and water was changed and more microcapsules added after 2 days. After 3 days, the experiments were terminated and the larvae from each treatment were washed and placed in 1-μm-filtered seawater for 24 hours, in order to clear the gut of microcapsules. The larvae were then washed, drained of excess water and frozen.

Protein-walled microcapsules containing ^{14}C glucose were also fed to *Hippopus hippopus* larvae. Experimental conditions were as described above with the exception that the larvae were 6 days old.

Larvae from each treatment were homogenised in distilled water and the homogenate separated into acid-soluble protein and lipid fractions by a modification of the method of Shibko et al. (1967). Each of the isolated fractions was assayed for its radioactivity on a LKB 1217 Liquid Scintillation Counter, using Beckman Ready Safe Liquid Scintillation Cocktail. The percentage distribution of radioactivity throughout the isolated larval tissue fractions was calculated.

Growth Experiment

A simple test diet of the composition shown in Table 1 was manufactured using two types of microcapsules. Protein-walled capsules were used to encapsulate the water-soluble nutrients, namely, protein and carbohydrate, and gelatin-acacia microcapsules were used to encapsulate the lipid component.

The culture apparatus consisted of 1.5-l plastic jars, which contained 1-μm-filtered seawater, containing 50 mg/l streptomycin sulfate, at 27 ± 1°C. Three-day-old *T. gigas* larvae were placed in the jars at a density of 6 larvae/ml. Three different feeding regimes were adopted: (1) 2×10^4 microcapsules/ml; (2) 2×10^4 algal cells/ml

TABLE 1. Composition of artificial diets.

Dietary component	Percentage composition by weight	Percentage composition of diet (by weight)
Protein-walled capsules		
Albumen (egg)	60	54
Sucrose	40	36
Gelatin-acacia capsules		
Cod liver oil	100	10

(*Isochrysis galbana*); and (3) starved. There were two replicates per treatment. Food was added to the jars daily, while every second day the larvae were washed, the jar disinfected and refilled with fresh filtered seawater. At each water change the larvae from each treatment were counted and percentage survival calculated. A small number of larvae was also preserved in seawater-formalin at each water change for subsequent shell measurements. When the larvae were 10 days old (pediveliger), they were washed and placed in beakers containing 1-μm-filtered seawater, to which were added zooxanthellae freshly isolated from adult *T.gigas* mantle tissue. The larvae were held under these conditions for 1 day, before being placed into plastic beakers, with 130 μm polyester mesh bases. The beakers were placed in suspended trays in a recirculating seawater system at James Cook University. Jars were stocked at a density of approximately 1 larva/7 mm^2 bottom area, and the beakers were covered with 50% shade cloth and placed in an outside tank, which had a canopy of 50% shade cloth.

After 5 days, the mesh base of each jar was washed with 1-μm-filtered seawater, dispensed from an atomiser spray gun, and the jars were then further inoculated with freshly isolated zooxanthellae as outlined above. Each jar was then washed every 3 days in an effort to reduce algal growth on the mesh bases. After 1 month the experiment was terminated, and the juvenile clams from each jar were counted and measured. Percentage survival from pediveliger (settlement) to 1-month-old juveniles was then calculated for each dietary treatment.

Results

Digestion Experiment

Tridacna gigas and *H. hippopus* larvae readily ingested the three types of microcapsules used in this study, as indicated by coloration of the gut (Fig. 2). Digestion of ingested microcapsules was demonstrated by the observed fading of the colouring once feeding had ceased. The fading of

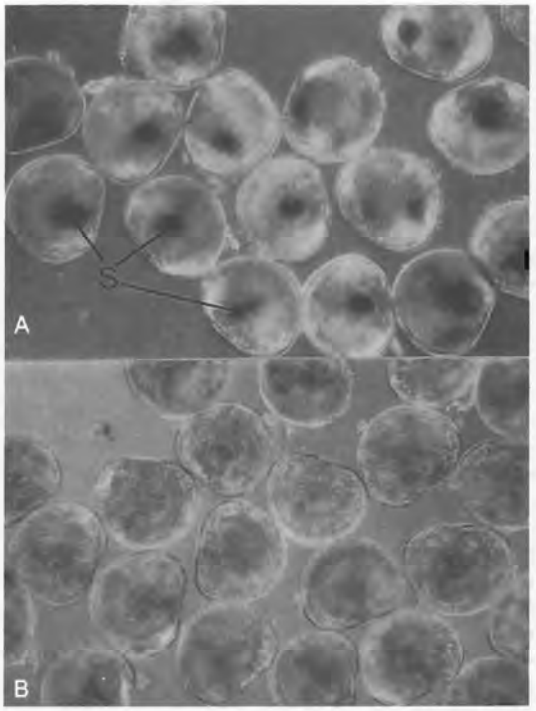

Fig. 2. A. *Tridacna gigas* larvae after feeding for 9 hours on stained lipid-walled microcapsules, showing coloured microcapsules in gut(s). B. Larvae 72 hours after termination of feeding on coloured microcapsules.

colour coincided with a decrease in the area of the gut containing stain, and also the percentage of the larvae with coloration to the gut. Observations on the coloration of the guts of the larvae at various times after feeding are summarised in Table 2. Larvae fed gelatin-acacia and lipid-walled microcapsules lost all coloration to their guts within 72 hours of feeding. However, most of the coloration disappeared within 48–60 hours after feeding, after which time the remaining faint coloration to the gut may have been caused by small staining of gut tissue and not the presence of microcapsules. Colour from alginate particles faded

TABLE 2. Digestion of stained microcapsules by *T. gigas* larvae.

Type of micocapsule	Time since feeding (hours)	% of larvae with stain	Degree of colouration
Gelatin-acacia	0	100	Large dark red stain to gut
	24	35	Smaller coloured area as above
	48	29	Smaller coloured area, pink in colour
	60	27	Very faint colour to small area
	72	0	No colour present
Lipid-walled	0	100	Large dark red stain to gut
	24	30	Smaller, paler coloured area
	48	25	Very small, pink areas to gut
	60	10	As above
	72	0	No colour present
Alginate particles	0	86	Pale purple colouration
	24	72	Smaller area than above, very pale colouration
	48	32	Small, very pale coloured areas
	60	0	No colour present
	72	0	No colour present

rapidly during the first 24 hours after feeding and disappeared totally after 60 hours. This may indicate that alginate particles are rapidly digested by giant clam larvae, possibly due to the lack of a capsule wall, which is present in gelatin-acacia microcapsules.

Assimilation of ^{14}C-Labelled Nutrients

The radioactivity of each of the isolated fractions from ^{14}C-nutrient-fed larvae is shown in Table 3. Some radioactivity was incorporated into all three isolated fractions from larvae in all treatments. In larvae fed ^{14}C glucose from protein-walled microcapsules, the highest percentage of radioactivity was found in the acid-soluble fraction. This fraction is composed of low molecular weight water-soluble nutrients including free amino acids and carbohydrate. Both *T. gigas* and *H. hippopus* possessed more than 60% of their total radioactivity in the acid-soluble fraction. A substantial fraction of the total activity, namely 22.8 and 38.96%, was also incorporated into the protein fraction of *H. hippopus* and *T. gigas* respectively. Little radioactivity was incorporated into the lipid fractions of both species when fed ^{14}C glucose.

Radioactivity from ^{14}C cholesterol, from both gelatin-acacia and protein-walled microcapsules, was also incorporated into the three isolated fractions of *T. gigas* larvae. Not surprisingly, in both diets, most of the radioactivity was found in the lipid fractions. Over 50% of the activity was present in the combined protein and acid-soluble fractions of larvae fed with gelatin-acacia microcapsules. However, the equivalent fractions in larvae fed with protein-walled capsules contained only 16.9% of the total activity.

Growth Experiment

All treatments showed high percentage survival through larval life to the settlement stage (Table 4). Algal-fed larvae had the lowest percentage survival of 82.4% over this period, while larvae fed the microencapsulated diet had the highest percentage survival of all treatments at 92.0%. Interestingly, starved larvae had a percentage survival of 86.2% which was greater than in the algal-fed larvae. High mortalities were evident in all treatments during the period from settlement and metamorphosis to 35 days (1 month from settlement). Algal-fed larvae had a survival of 1.7% while 1.68% of the

TABLE 3. Radioactivity incorporated into larvae tissue fractions after feeding on microcapsules containing ^{14}C-labelled nutrients.

	Diet							
	A[a]		B		C		D	
Tissue fraction	Activity[b]	% Activity	Activity	% Activity	Activity	% Activity	Activity	% Activity
Acid soluble	2970	68.55	117	26.59	9216	60.88	86	2.37
Protein	988	22.80	118	26.81	5898	38.96	528	14.58
Lipid	374	8.6	205	46.59	22	0.14	3005	83.03
Total (CPM/mg wet wt)	4332		440		15136		3619	

[a] A = *H. hippopus* larvae fed ^{14}C-glucose in protein walled microcapsules;
B = *T. gigas* larvae fed ^{14}C-cholesterol in gelatin-acacia microcapsules;
C = *T. gigas* larvae fed ^{14}C-glucose in protein-walled microcapsules;
D = *T. gigas* larvae fed ^{14}C-cholesterol in protein-walled microcapsules.
[b] Counts per minute (uncorrected)/mg wet weight.

TABLE 4. Percentage survival and shell size of *T. gigas* larvae at different stages through the growth trial.

Treatment	Time (days) since start of experiment[a]	% Survival	Mean shell length (μm ± SD)	Mean shell height (μm ± SD)
Algae-fed	2	100	185.66(±3.6)	153.66(±2.0)
	4	86	194.32(±6.9)	164.00(±7.2)
	6	82.41	198.16(±7.9)	170.64(±7.2)
	7	-	203.28(±4.4)	172.64(±5.6)
	35	1.7	504.50(±36.4)	453.96(±34.2)
Microcapsule-fed	2	100	181.60(±4.3)	151.60(±3.1)
	4	92.61	184.60(±6.7)	153.12(±6.8)
	6	92.05	189.00(±5.9)	158.16(±4.9)
	7	-	193.66(±4.9)	162.32(±5.2)
	35	1.68	454.93(±15.2)	406.96(±12.9)
Starved	2	94.37	179.28(±5.1)	148.64(±4.9)
	4	90.62	183.50(±5.7)	151.66(±4.0)
	6	86.21	183.50(±3.4)	152.00(±2.2)
	7	-	-	-
	35	0	-	-

[a] Experiment started when larvae were 3 days old.

microcapsule-fed larvae survived to this stage. No starved larvae survived to this stage. The figures in Table 4 represent percentage survival from the start of the experiment; however, from day 10 to day 35, 2.14% of the algal-fed larvae survived while 1.82% of the microcapsule-fed larvae survived. At the end of the experiment (35 days) both algal-fed and microcapsule-fed juveniles had large numbers of zooxanthellae visible throughout their tissues.

Far greater shell growth was shown by the fed larvae compared to starved larvae, through larval development. Of the fed larvae, the algal diet promoted greater shell growth than shown by the larvae fed the microencapsulated diet. The greater shell growth of algal-fed larvae compared to capsule-fed larvae is also shown in the mean postlarval shell lengths of 504.5 and 454.4 μm respectively.

Discussion

The results of this study demonstrate that microcapsules are readily ingested by giant clam larvae, and their nutrients assimilated. Observations on digestion of capsules is in agreement with the findings of Chu et al. (1982), who fed coloured microcapsules to larvae of oysters (*Crassostrea virginica*). They showed that oyster larvae readily ingested both gelatin-acacia and protein-walled microcapsules. Indeed, growth of larvae fed a diet of cod liver oil encapsulated in gelatin-acacia was as good as those fed an algal diet. In *C. virginica*, gelatin-acacia capsules were more easily digested

than protein-walled capsules, having digestion times of approximately 48 and 72 hours respectively (Chu et al. 1982). Digestion of protein-walled and glycopeptide microcapsules by stomach juices of *Crassostrea gigas* has also been demonstrated (Gabbott et al. 1976).

Assimilation of ^{14}C-labelled nutrients by both *T. gigas* and *H. hippopus* larvae demonstrated that microencapsulated nutrients are readily metabolised and incorporated into larval tissue. ^{14}C-glucose was metabolised by both species to incorporate radioactivity into the three biochemical fractions isolated. The high activity of the protein fractions indicates de novo synthesis of nonessential amino acids, and their subsequent incorporation into tissue protein. It is likely that ^{14}C-labelled free amino acids contributed to the high activity of the acid-soluble fractions. However, high activity in this fraction would be expected because it also contains carbohydrate. Very small amounts of radioactivity were also present in the lipid fraction.

In larvae fed diets containing ^{14}C cholesterol, differences in the percentage of total radioactivity contained in each of the isolated fractions are evident between the two diets used. When ^{14}C cholesterol was presented in gelatin-acacia encapsulated cod liver oil (100% lipid diet), then approximately half of the total recovered activity was from the lipid fraction, while the acid-soluble and protein fractions each contained approximately 26% of the activity. However, when ^{14}C cholesterol was presented in protein-walled microcapsules containing a diet based on chicken egg yolk, with approximately 40% lipid in the diet, then 83.03% of the radioactivity recovered was in the lipid fraction, 14.5% in the protein fraction and only 2.37% in the acid-soluble fraction. These results indicate that in giant clam larvae, the assimilation and metabolism of dietary nutrients may be modified according to the biochemical composition of the diet.

The results of the growth trial have shown that *T. gigas* larvae are able to develop normally and reach settlement without an exogenous food source, however none of the starved larvae survived to 1 month beyond settlement. Lipid is the main energy reserve in giant clam larvae throughout development, and the main energy source for metamorphosis (Southgate, This Monograph). It is likely that unfed *T. gigas* larvae drew heavily on lipid reserves which allowed development to settlement. However, the remaining lipid reserves present at settlement may have been insufficient to provide the energy needed to successfully achieve metamorphosis and early postlarval growth.

Although differences in the percentage survival between the algae and microcapsule-fed larvae were small, differences in growth (shell length) were evident. Differences in growth are likely to be a result of the nutritional composition of the diets. The algal diet would be expected to have a wider variety and better balance of nutrients than the encapsulated diet.

Recently, microcapsules have been used to present diets to bivalves and bivalve larvae in a number of studies (Chu et al. 1982; Teshima et al. 1982; Langdon and Siegfried 1984; Langdon and Bolton 1984; Laing 1987; Chu et al. 1987). However, studies with bivalve larvae have been limited. Chu et al. (1987) achieved metamorphosis of *Crassostrea virginica* on a microencapsulated diet, and were the first to report metamorphosis of bivalve larvae fed an artificial diet. The present study is believed to be only the second report of a successful microencapsulated diet for bivalve larvae.

The results of this study are very encouraging when it is considered that the artificial diet used was very simple, and took no account of optimum dietary proportions of lipid, protein and carbohydrate or indeed, the source of these nutrients. No account was taken either of the vitamin or trace element composition of the diet. It is likely that once an optimum diet has been developed for giant clam larvae, then growth and survival of larvae fed artificial diets may well exceed that achieved on algal diets.

In this study, microcapsules have been demonstrated to be an effective means of presenting dietary nutrients to giant clam larvae and may be of great value in investigating the nutritional requirements and metabolism of giant clam larvae. The development of a successful artificial diet of optimum composition would replace the need for algal culture as part of giant clam hatcheries. The use of an 'off-the-shelf', dried, microencapsulated diet would allow giant clam hatcheries to be established in isolated locations, without a dependence on specialised equipment or personnel, thereby greatly reducing hatchery costs.

Acknowledgments

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Postmetamorphic Feeding in Clams: Relevance to Tridacnidae

R.G.B. Reid and J.J. King*

Abstract

In some adult bivalves and most known juvenile bivalves pedal-palp feeding is an important phenomenon. *Panope abrupta*, the commercial geoduck clam of the North Pacific, is presented as a model for juvenile bivalve feeding behaviour. For a period of about 12 weeks after metamorphosis it collects food by means of the protracted ciliated foot, using the labial palps to manipulate and partially sort the contents of oral food boluses. Due to a lag in the development of the gills and siphons, suspension feeding does not contribute to nutrition until late in juvenile development.

The universality of pedal-palp feeding in bivalve juveniles and some adult bivalves suggests its significance in juvenile tridacnids. For a week after metamorphosis these are almost entirely heterotrophic and heterotrophy persists throughout adult life, though supplemented greatly by symbiotic autotrophy. Since mortality in cultured giant clam larvae is high at metamorphosis this heterotrophic stage is crucial. If pedal-palp feeding is used at this stage care will need to be taken with the physical properties of the substrate and the quality of sediment food for juveniles.

An earlier discussion of the aquacultural nutrition of bivalves stressed the need to examine each cultured species on its own merits, because of the variability of feeding processes, particle-sorting, and digestive cycles (Reid 1983). The individual features of heterotrophy in the Tridacnidae are well established (Morton 1978; Reid et al. 1984). Moreover, the nutritional and evolutionary impact of symbiosis with zooxanthellae, while not entirely unique, is so strongly marked that giant clams have been placed in a niche of specialised investigations that sometimes has little reference to the generalities of bivalve biology.

In the following presentation we will remark upon one such generality that refers to the problem of postmetamorphic, juvenile nutrition and survival in bivalves: namely the occurrence in most juvenile bivalves that has been investigated of a pedal-feeding mechanism that sustains them until the inhalant siphon and ctenidial food grooves have become functional for suspension feeding. The availability of deposited food, and the physical quality of the substrate are related to this phenomenon. Juvenile mortality in all bivalves is high, and it is often conceded that starvation is a major factor. Therefore some consideration of the generalities of feeding behaviour is always justified.

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Anterior Inhalant Filtration and Pedal Feeding

Anterior inhalant filtration, as seen in the Nuculidae (Protobranchia) is generally regarded as a primitive condition in bivalves (Yonge 1939). The labial palp apparatus accepts both detritus and suspended food particles (Reid and Brand 1986). The foot does not, however, appear to have any direct role in food collection (Stasek 1961). Pedal feeding is rare in large adult bivalves, the best known case being that of *Fimbria fimbriata* (Morton 1979). This benthic denizen of coral sands has a diet of suspended particles that are taken by an anterior feeding current, and detrital particles that are collected by the foot (Fig. 1). Reid and Slack-Smith (1988) speculate that this species, like all known

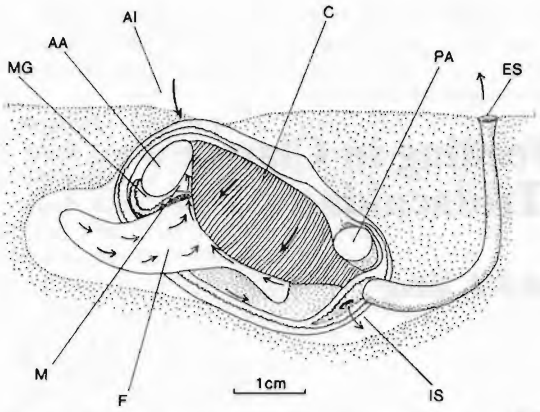

Fig. 1. *Fimbria fimbriata*, after Morton (1979). AA = anterior adductor muscle; AI = anterior inhalant current; C = ctenidium; F = foot; IS = 'inhalant' siphon where pseudofaeces are removed; M = position of mouth; MG = mantle gills; PA = posterior adductor muscle.

members of the related Lucinidae, has a sulfide-oxidising symbiosis with ctenidial bacteria. Small, carnivorous bivalves belonging to the Septibranchia possibly manoeuvre live zooplanktonic food into the mouth once it has been seized by the raptorial, siphonal apparatus (Bernard 1984).

Corbicula fluminea (Corbiculacea) is also a pedal feeder. This freshwater species uses the foot as an anchor in fast-flowing streams and collects detritus from the substrate by means of pedal ciliary currents (Fig. 2a). When placed on a hard surface with a film of deposit material *Corbicula* extends the foot and ingests deposit particles by pedal cilia that are activated on the down side of the foot (Fig. 2b) (Reid and McMahon, unpublished data).

It is instructive to note that *Corbicula* has been the object of close scrutiny by numerous investigators, because of its population explosion in the southern watersheds of the United States, and because of its awkward habit of clogging-up the water-cooling systems of nuclear power stations. Any specimen of *Corbicula* will demonstrate pedal browsing behaviour as soon as it is placed on a hard surface, and this must have been seen by hundreds of zoologists. Yet only R. McMahon of the University of Texas at Arlington, and, at his prompting, R.G.B. Reid, have perceived the significance of the phenomenon. We believe that the problem of seeing but not perceiving is apposite to juvenile bivalve feeding behaviour.

Pedal feeding has also been observed in *Mysella bidentata* by O'Foighil (1981). This minute bivalve protrudes the foot posteriorly and then swings it anteriorly (Fig. 3). During this process particles adhere to the flanks of the foot and are carried

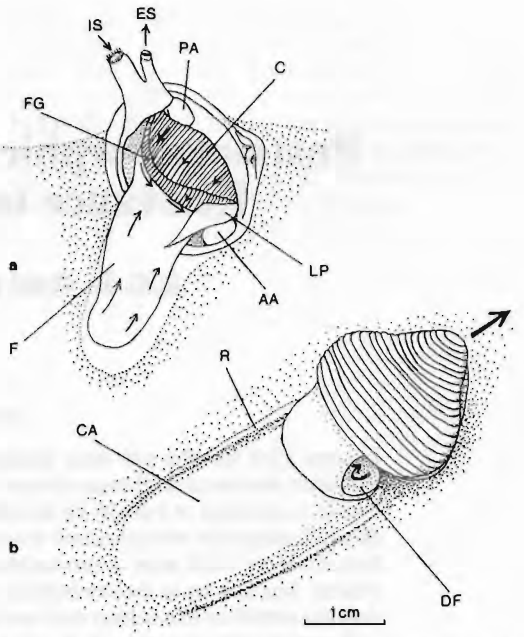

Fig. 2. *Corbicula fluminea*. *2a*. Feeding mode in soft substrates. Anatomical details after Britton and Morton (1982). *2b*. Detritus feeding on hard surface with a deposit film. Large arrow indicates direction of movement brought about by leverage of foot. Area shown cleared in 12 min. Both diagrams to approximately the same scale. AA = anterior adductor muscle; C = ctenidium; CA = cleared area; DF = down side of foot; ES = exhalant siphon; F = foot; FG = food groove; IS = inhalant siphon; LP = labial palp; PA = posterior adductor muscle: R = trail of rejected large particles and sediment dislodged by valves.

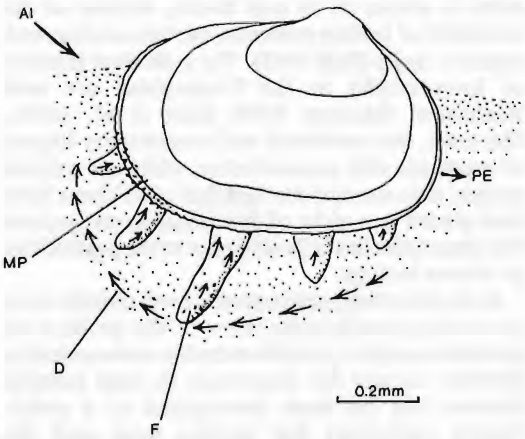

Fig. 3. *Mysella bidentata*, after O'Foighil (1981). The foot is shown in the sequence of positions and protractions during pedal feeding. AI = anterior inhalant current; D = direction of foot movement; F = foot; MP = mantle edge with adhering particles; PE = posterior exhalant current.

dorsally by the pedal cilia. At the limit of its anterior extension the foot is withdrawn, and the larger grains of substrate adhering to it are scraped off as they contact the valve margins. During active locomotion particles are carried along the flanks of the foot from anterior to posterior and are deposited behind the animal in a pair of mucus strings. However, at irregular intervals, the foot is retracted, carrying its burden of adhering particles into the mantle cavity. O'Foighil also notes that the tip of the particle-laden foot comes into contact with the large, mobile, labial palps, and that a bolus of food can be discerned, through the translucent valves, rotating between the palps.

The juvenile pedal induction of the anterior inhalant current containing particulate food has been preserved paedomorphically in a number of other minute bivalves such as *Lasaea rubra* and *Turtonia minuta* (Oldfield 1955). In all likelihood, a perceptive examination of more of these types of bivalves will reveal pedal feeding.

Feeding in Juvenile Bivalves

The foot of postmetamorphic juvenile *Mytilus edulis* creates an active feeding current that brings food particles into contact with the inner surfaces of the labial palps (Bayne 1971). At this stage the gills are not large enough to create a posterior inhalant current nor to collect food.

In juvenile *Macoma balthica* pedal ciliation induces the anterior inhalant current, before the relative importance of the gills and palps has been established (Caddy 1969). Aabel (1983) has shown that the foot of juvenile *Abra alba* brings particles into the mantle cavity during the digging cycle and when at rest. Contraction of the foot during digging brings in particles that have adhered to its margins and sucks in some water and particles.

Panope abrupta is now the bivalve species whose juvenile feeding behaviour has been most extensively studied. King (1986) examined the juvenile stages of this species by a variety of methods including direct light microscopy, scanning electron microscopy, videomicroscopy, and time-lapse photography. He also measured growth rates under different substrate conditions.

A denizen of the North Pacific, ranging from the east coast of Japan and Alaska down the west coast of North America to Baja California, *Panope abrupta* is a 'true' giant clam, in the sense that it burrows to the depth of 1 m in sand, and reaches a weight of 9 kg. The meat is much sought after in Japan, and so it has been the subject of a recent intense fishery that has placed heavy pressure on wild stocks. In the 1984 season in British Columbia, 3480 t were landed at a value of CAD$2.9M (Harbo et al. 1986). An experimental aquaculture project at Point Whitney Shellfish Laboratory in Washington found that juvenile mortality reached 100% (Shaul 1981) and this motivated King's study at the University of Victoria.

After metamorphosis at 4 weeks, *Panope* juveniles use pedal-palp feeding through the 6 weeks of byssal plantigrade development, and into the juvenile plantigrade stage, at least until deep-burrowing behaviour is established at about 12 weeks after metamorphosis. Indirect evidence from juvenile growth rates indicates that pedal-palp feeding remains important through the juvenile plantigrade stage. In the pedal-palp feeding mode the organism lies partially on its side and the foot is extended posteriorly through the pedal gape and slowly swept anteriorly (Fig. 4). At the limit of anterior protraction the foot is withdrawn. As the extended foot comes into contact with the substrate it secretes mucus that binds the particles of deposit material and sand grains ranging in size from 5 μm to 150 μm. Pedal cilia sweep the mucus strings dorsally so that they frequently form a girdle at the base of the foot. When the foot retracts, the folding of the epithelium loosens the mucus-bound particles. An oral current generated by the cilia of the labial palps sweeps the food into the bolus that rotates in a vortex in the vicinity of the mouth. Passive contact between the labial palps and the base

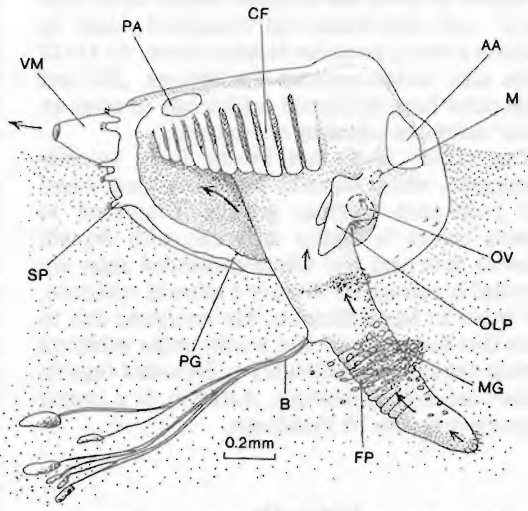

Fig. 4. *Panope abrupta*, late byssal plantigrade juvenile, after King (1986). AA = anterior adductor muscle; B = byssus; CF = ctenidial monofilament; FP = folded area of propodium; M = position of mouth; MG = mucus girdle with bound particles of food and sand; OLP = outer labial palp; OV = oral vortex; PA = posterior adductor muscle; PG = posterior end of pedal gape; SP = sensory papilla; VM = valvular membrane (a protoexhalant siphon).

of the foot, and muscular flicking motions of the palps, also free the mucus strings.

Dense sand grains in the food bolus are rotated and come into contact with the inner surfaces of the outer palps several times before being centrifuged off and rejected as pseudofaeces. At this stage of development there are no ciliary sorting areas on the palp, but physical sorting ensures that the particle size ingested does not often exceed 50 μm. Occasionally the foot is reflexed and the propodium stuffs the food bolus into the oesophagus.

This feeding cycle may be repeated as often as 50 times over a period of 10 min. King (1986) remarks that 'Propodial food collection occupies much of the total behaviour of juveniles and is a stereotypical pattern which cannot be confused with burrowing.' Where there is adequate deposit material mixed with the mineral substrate particles the juveniles remain in the same area, excavating the surface. If there is no suitable food, or if the clams are on a hard surface, they move rapidly. For up to 12 weeks of postmetamorphic juvenile existence individuals are byssally attached to sand grains, but the byssus threads can be extended up to 10 cm, or released, so they do not hinder feeding behaviour.

In the early byssal plantigrade the ctenidial filaments are pectinate and have no food-collecting ability. At about 5 weeks into this stage the filaments reflex and grow ventrally, forming a ciliated food-groove at their tips. By this time they are sufficiently developed to divide the posterior mantle cavity into supra- and infrabranchial chambers, and to establish a weak, posterior inhalant flow. At 11–12 weeks after metamorphosis the siphons, gills and labial palps have developed sufficiently to form an 'adult' suspension-feeding apparatus.

King (1986) finds that in the early juvenile plantigrade, which burrows only occasionally and uses pedal-palp feeding, growth is greatest in animals raised in coarse sediment with deposit material. It is next best where suspended algae are provided in containers without a mineral substrate, and worst in fine sediments. He interprets this to mean that for most efficient nutrition the substrate particle size and the availability of deposited organic matter, are both important. Aeration in a coarse substrate may also be significant.

Tridacnidae

As with all other aquacultured bivalves, Tridacnidae have high mortality rates between spawning and the late juvenile stage (summarised by Fitt et al. 1984). Trochophore and pediveliger biology has been studied in some detail, with an emphasis on the acquisition of symbiotic zooxanthellae (Fitt and Trench 1980, 1981; Fitt et al. 1984). Symbiont transmission is not holobiotic and the larvae will metamorphose in the absence of suitable symbionts. Where the latter are available they become established in the siphonal tissues of *Tridacna squamosa* 2–9 days after metamorphosis (Fitt and Trench 1981). Heslinga et al. (1984) report that symbionts are clearly visible in the siphonal tissues of *T. gigas* 11 days after metamorphosis.

As Fitt et al. (1984) point out, exogenous nutrients encourage growth and survival of pediveligers and are likely necessary for the juveniles. Late juveniles can survive for 6 months in micropore-filtered seawater (Fitt and Trench 1980), and Beckvar (1981) showed growth variations in *T. squamosa* commensurate with available sunlight. Therefore the portion of the life-cycle to which general observations on bivalve pedal feeding might be relevant would be from metamorphosis to whatever juvenile stage can be totally sustained by symbiosis: perhaps only a short but crucial period of no more than a week or so. Fitt et al. (1984) conclude that high mortality at the transition from pediveliger to juvenile is likely due to changes in the mode of acquiring nutrition, and the nutritional requirements at this stage 'would *not* be expected to be very different from that of nonsymbiotic clams.'

Observations on the byssate and late juveniles of tridacnids have probably been numerous but casual. Yonge (1980) notes that crawling behaviour in 5-mm *T. crocea* juveniles resembles that of *Mytilus edulis*, with intermittent byssal attachment and roaming by pedal locomotion. These individuals have an adult form except for the long, mobile foot. This species may continue to move for 6 months before becoming permanently attached. Heslinga et al. (1984) note similar behaviour in *T. squamosa*.

It is significant that most observations and experiments involving pediveligers and early juveniles have been conducted in glass vessels. Moreover mass culture procedures pay no regard to substrate quality at the early juvenile stage (Heslinga et al. 1984). If tridacnids, like most other bivalves, employ pedal-palp feeding immediately after metamorphosis, they would require a particulate substrate with physical properties consistent with their feeding behaviour: indeed such behaviour might not be observable under any other circumstances. If pedal feeding does occur, physical properties of the substrate particles such as size, density, aeration and cohesion with natural and synthetic food particles would require consideration. Here is a possible opportunity for the use of appropriately designed, sedimentary microcapsules. Yamaguchi (1977) concluded that a breakthrough in the handling of early juveniles was required for final success in large-scale aquacultural methods for tridacnids. We present one such hypothetical 'handling' alternative.

Acknowledgments

This presentation is based on the PhD thesis of the second author and an unpublished 1985 discussion paper by the first author arising from a study of *Corbicula*. The first author is grateful to Bob McMahon for introducing him to that organism and we wish to thank Diarmaid O'Foighil for his contribution to the discussion and for the opportunity to cite his thesis work on *Mysella*. Travel to the Townsville workshop was supported by a University of Victoria Travel Grant to R.G.B. Reid, and by an operating grant of the Canadian Natural Sciences and Engineering Research Council.

Role of Zooxanthellae in the Mariculture of Giant Clams

William K. Fitt*

Abstract

Interest in the mariculture of giant clams (family Tridacnidae) has blossomed over the last 15 years, initially due to discoveries concerning their reproductive and developmental physiology. Recent progress in the application of mariculture techniques has outstripped our knowledge of the basic physiology of tridacnids, especially understanding the process occurring between the symbiotic zooxanthellae and the clam host. In this presentation aspects concerning the physiology of zooxanthellae symbiosis that have relevance to mariculture of giant clams are reviewed.

Establishment of a Symbiosis

SINCE tridacnids do not pass their symbionts to the next generation via the egg (LaBarbera 1975; Jameson 1976; Fitt and Trench 1981), each baby clam must acquire zooxanthellae from its environment. During 'infection' of veliger and juvenile clams, motile zooxanthellae are apparently attracted to their potential hosts by dissolved nitrogen compounds, such as ammonium or certain amino acids (Fitt 1984, 1985a). Unlike phytoplankton food species, zooxanthellae taken into the stomachs of veliger clams remain there for days, suggesting that they are not digested by the clams (Fitt et al. 1986). Larval clams fed freshly isolated zooxanthellae before metamorphosis have higher growth and survival rates through metamorphosis than starved clams, showing that they derive nutrients from the zooxanthellae in their stomach (Fitt et al. 1986). The presence of zooxanthellae in the stomachs of veligers before metamorphosis facilitates establishment of a symbiosis (entry and growth of the zooxanthellae in the mantle tissues) and increased growth after metamorphosis (Fitt et al. 1986).

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Photosynthesis and Photoadaptation

Zooxanthellae in the clam respond to light, giving classic photosynthesis vs light intensity (PI) curves (Fisher et al. 1985). However this response is dependent on the size of the clam: while small clams reach maximal photosynthetic rates at one-quarter of maximum sunlight intensities in air, larger clams never reach their maximal photosynthetic rates because of the extensive shading of many of their zooxanthellae by both clam tissue and other zooxanthellae. Therefore small clams in mariculture may be kept in shaded land-based nurseries or in oceanic habitats with lower light intensities without reducing their maximal growth rates, while larger clams need maximum exposure to sunlight to achieve their maximum potential growth rates. Photoadaptation of zooxanthellae in clams to low light (Mingoa, This Monograph), by increasing numbers of zooxanthellae per clam or the amount of light-harvesting pigments per zooxanthella, is effective in maximising photosynthesis (and therefore clam growth) in small clams in low-light habitats, but probably not very effective in large clams because of the extensive shading of many of the zooxanthellae.

Differences in Zooxanthellae

Genetically distinct species of zooxanthellae of the genus *Symbiodinium* have recently been described

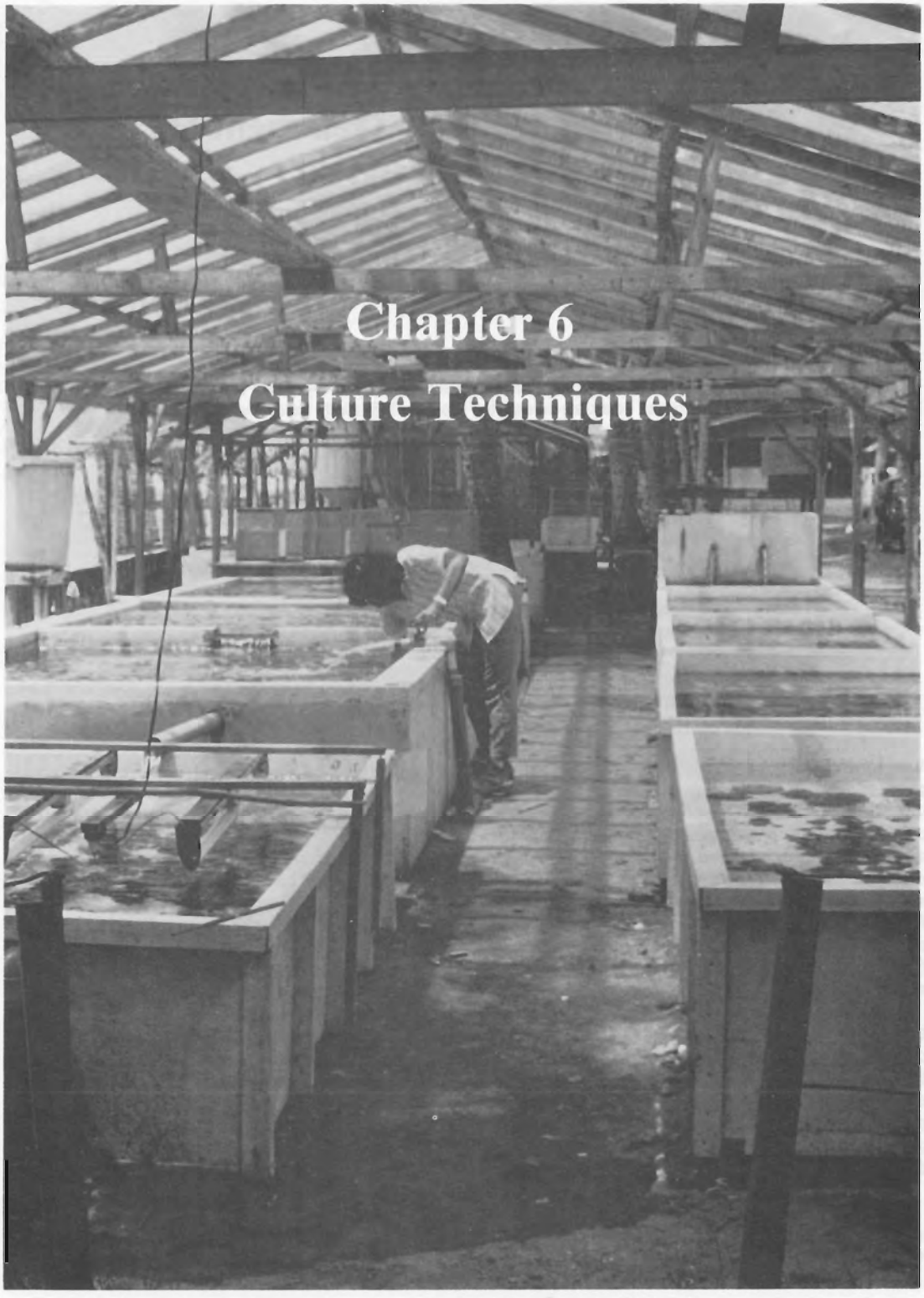
(Blank and Trench 1985). While all types of *Symbiodinium* are capable of establishing a symbiosis with tridacnids, symbiosis with some zooxanthellae leads to higher growth and survival rates than others (Fitt and Trench 1981: Fitt 1985b). Selection of optimal zooxanthellae for mariculture of specific tridacnid species in particular environments is currently being investigated. Preliminary evidence indicates that fast-growing types of zooxanthellae (in the host) also give faster growth rates of the clams (Fitt 1985b). Introduction of 'optimal' zooxanthellae into larval tanks before metamorphosis is the preferred method of clam acquisition of zooxanthellae in mariculture. Manipulation of type of zooxanthellae living in symbiosis with tridacnids may be achieved by expulsion of 'suboptimal' zooxanthellae by treating clams with warm water, and subsequent reintroduction of 'optimal' zooxanthellae.

Nutrients

Zooxanthellae in tridacnids may be nutrient-limited. Introduction of dissolved inorganic nutrients such as nitrogen (ammonium or nitrate) (see Wilkerson and Trench 1986), phosphate, and sulfate may increase either photosynthetic rates or numbers of zooxanthellae (or both), thereby increasing the amount of photosynthate available to the host for growth (see Alcala, This Monograph).

Conclusion

Since one of the major constraints in the mass culture of tridacnids is space in the land-based nursery phase, optimising growth and survival of the larvae and juveniles by taking advantage of physiologically optimal conditions of the zooxanthellae symbiosis is one way of efficiently utilising available space and maximising production.



Chapter 6
Culture Techniques

Testing an Antifouling Treatment for Ocean-Nursery Meshes

J.S. Lucas*

Abstract

Controlling the fouling of protective meshes during the ocean-nursery phase of giant clam mariculture can be a time-consuming process. This study tested the effectiveness of coating meshes over trays of juvenile *Tridacna gigas* with Flexgard, a commercial antifouling preparation. Flexgard did not cause clam mortality, nor was there evidence of sublethal effects in terms of reduced clam tissue or shell growth. After 1 month of immersion, Flexgard-coated meshes at a subtidal site were substantially less fouled than uncoated meshes and similar to scrubbed meshes. After 3 months all meshes, scrubbed, untreated and Flexgard-coated, were similarly lightly fouled. By this stage the Flexgard coatings were partly detached from the mesh surfaces and algae were growing directly on the coating. Thus, Flexgard is not suitable for use on these protective meshes as antifouling is required for a year or more, the duration of the ocean-nursery phase. The most economic method of controlling fouling is drying the meshes by removing them from the sea or by using intertidal sites.

WHEN juvenile clams are about 20 mm shell length at 6+ months of age they are transferred to the field in mesh enclosures, a stage of culture which has been called the ocean-nursery phase and which lasts for a year or more (Crawford et al. 1987). The mesh enclosures are necessary to protect the small, thin-shelled clams from a variety of predators, e.g. fishes, crabs, octopods and gastropods. Several different kinds of mesh enclosures have been tested (Barker et al., This Monograph) as well as plastic and wire meshes.

One not-unexpected problem with the meshes is their progressive accumulation of fouling organisms, especially algae. This results in reduced light and reduced circulation of water to the enclosed juvenile clams, both of which are inimical to growth. Heavy fouling of plastic meshes on boxes containing juvenile *Tridacna gigas* at about 5 m depth at Orpheus Island Research Station (OIRS), Great Barrier Reef, resulted in heavy mortality of these clams during winter 1985 (unpublished data). This was apparently because light levels within the boxes, already reduced by silty water and depth, were reduced to lethal levels by the fouling.

The meshes may be regularly scrubbed to control fouling. This has been done routinely at the Micronesian Mariculture Demonstration Center (MMDC), Palau, and at OIRS. However, it becomes a very time-consuming activity as the ocean-nursery holdings increase. At MMDC the meshes are now changed at 4–6-month intervals and the fouled meshes dried before reuse (Heslinga et al. 1986). At OIRS the ocean-nursery phase of giant clam culture has been developed in the intertidal zone because of the antifouling effect of regular exposure of meshes to air (Lucas 1987; Crawford et al. 1987).

Another potentially economical method of controlling fouling is to treat the meshes with an antifouling coating. Many of the commercially available antifouling coatings are not suited for application to flexible, synthetic surfaces such as the plastic meshes used for the clam enclosures.

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However, Flexgard (manufactured by Flexabar Corporation, 140 Walnut St., Northvale, NJ 07647, USA) is an antifouling coating that is a waterbased latex. It is flexible and, according to the manufacturer, has 'excellent adhesion to synthetic and natural fibers.' The active constituent of Flexgard is not indicated in the manufacturer's literature. It is recommended by the manufacturers for use with pound and trap nets, but not specifically for heavier meshes such as are used for protective coverings of juvenile clams.

This paper describes a study to test (1) the effectiveness of Flexgard in controlling fouling on ocean-nursery meshes, and (2) the toxicity of Flexgard to juvenile giant clams.

Materials and Methods

The study was conducted with juvenile *Tridacna gigas* obtained from a spawning at OIRS in October 1985. They were 1 year old and mostly had shell lengths within the range 30–40 mm at the commencement of the study. The clams were individually tagged using small pieces of plastic tape of various colours and having single letters or numbers on them. The tags were stuck onto one valve using an underwater epoxy adhesive.

Plastic trays covered with 26 mm plastic meshes and attached to wire mesh substrates were used. Each contained initially 25 tagged clams on a substrate of gravel chips. This is the same unit as used in other ocean-nursery studies at OIRS (e.g. Crawford et al. 1988, see Fig. 1). Two different treatments and a control were used: (1) mesh coated with Flexgard, without scrubbing; trays containing clams; (2) mesh uncoated, but with twice-weekly scrubbing; trays containing clams; and (3) control — mesh uncoated and not scrubbed; no clams in trays.

The effect of fouling on light transmittance through the meshes was measured in situ using an integrating quantum radiometer with underwater sensor and expressing the light reading below the mesh as a percentage of the ambient level. The Control meshes showed the degree of fouling and hence light reduction where no antifouling measures were taken. (No clams were used in the controls because it was anticipated that they would all die, at least at the subtidal site.) Treatment 2 served as a comparison of the effectiveness of scrubbing versus Flexgard (Treatment 1) in reducing fouling and as a control for the survival level of clams in the trays with Flexgard. Thus, greater mortality in Treatment 1 (Flexgard), especially early in the study before fouling levels could affect survival, would indicate that Flexgard is toxic to juvenile giant clams.

Two trays were used for each treatment and controls, and the experiment was repeated at two sites in Pioneer Bay in front of OIRS. One site was subtidal and the other intertidal (the same sites as used in Barker et al., This Monograph). Thus, the experiment consisted of two sites × two treatments (+ controls) × two trays at each treatment (+ controls) × 25 clams per tray (= 200 clams).

Flexgard was painted onto the Nylex meshes, which consisted of high-density polyethylene. It took two coatings to get a complete coverage of the outer surfaces of the meshes.

The shell length and wet weight (including tag) of each clam were measured at the commencement of the study (November 1986) and again at the end of the study (February 1987).

Results

There was very little fouling of the control meshes at the intertidal sites after the first month (Fig. 1), such that light transmittance was 74% compared to the initial level of 70%. Thus, no effect of either Flexgard treatment or scrubbing on fouling or light transmittance could be observed. The apparent slight increases in light transmittance through the meshes at this site, compared to the original values, must be an artifact of some irregularity in the response of the underwater radiometer. This does not negate the validity of the relative readings of the two treatments compared to the control.

After a month at the subtidal site the control meshes showed a marked reduction in light transmittance, down to 48%, due to fouling (Fig. 1). There was little change in light transmittance through the Flexgard-treated and scrubbed meshes, because they had little fouling. This showed the initial effectiveness of Flexgard as an antifouling coating.

After 3 months of exposure, however, all meshes at both sites had low levels of fouling and light transmittance levels were all within the range 60–70% and not significantly different (two-way ANOVA: treatment effect $P > 0.1$; locality effect $P > 0.1$). Thus, no antifouling effect of the

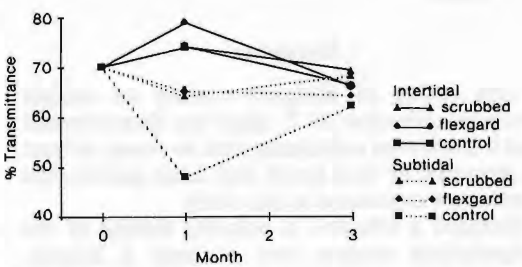

Fig. 1. Variation in percent light transmittance through ocean-nursery meshes versus period of exposure.

TABLE 1. Percent survival and growth of juvenile clams after 3 months under meshes with Flexgard coating or scrubbing. Values in parentheses are standard deviations.

	Intertidal	Subtidal
Flexgard treated meshes		
Percent survival	94	98
Growth increment:		
Shell length (mm)	27.20(3.50)	23.12(5.00)
Wet weight (g)	20.61(5.34)	15.66(5.85)
Cleaned meshes		
Percent survival	100	84
Growth increment:		
Shell length (mm)	29.22(4.05)	20.74(6.23)
Wet weight (g)	20.37(6.39)	11.63(5.12)

Flexgard coating was evident at this stage. The coating would need to be very effective in reducing fouling to have significantly affected light transmittance compared to the low-fouled controls.

General observations of the Flexgard coatings after 3 months showed that they had partly detached from the mesh surface in many places and that there were algae growing directly on the coatings. The experiment was terminated at this point because of the deterioration of the Flexgard coatings.

Survival and growth of the juvenile clams in the two treatments are shown in Table 1. There was no evidence of any toxicity of Flexgard to the juvenile clams under these conditions. The survival rates in the Flexgard treatments were slightly higher than in the scrubbed mesh treatments. Furthermore, there was no evidence of sublethal toxicity in terms of retarded growth. In two-way ANOVA analyses there were no significant effects of Flexgard vs scrubbing treatment on shell length increment ($P > 0.1$); while wet weight increments were significantly greater for the Flexgard treatment compared to scrubbing ($P < 0.05$). The significant effect of Flexgard treatment on wet weight increment was mainly at the subtidal site (Table 1). There were also highly significant intertidal vs subtidal effects (shell length increment $P < 0.001$; wet weight increment $P < 0.001$).

Discussion

This testing of Flexgard coating on meshes protecting juveniles of *T. gigas* has demonstrated that it is not even sublethally toxic to clams, at least as measured by shell length and tissue growth, the parameters considered in this study.

Flexgard is effective in reducing fouling of the polyethylene meshes over at least a month. However, the deterioration of the Flexgard coating after 3 months and algal growth directly on the coating after this period suggest that Flexgard's antifouling properties are limited in the long term. The period of ocean-nursery culture is a year or more and so an effective antifouling treatment would need to give much longer protection than afforded by Flexgard in this test.

Flexgard could be used on meshes that are exchanged after several months use in the ocean-nursery, as at MMDC. In this way the period between mesh changes could be prolonged. However, the deterioration of the Flexgard coating on the polyethylene mesh means that the coating would have to be renewed before the meshes were reused. This would involve cleaning dried fouling off the meshes before renewing the Flexgard coating and it would be a time-consuming and therefore probably uneconomical procedure.

At this stage, the most economic method of controlling excessive fouling of ocean-nursery meshes is to regularly dry the meshes to kill the fouling. This is done either by removing them from the sea (MMDC) or by using intertidal sites where the meshes dry out at low tides (OIRS).

Two points arise as sidelines of this study. One is the greater growth rates obtained in intertidal culture compared to subtidal culture (Table 1). This confirms the observations made of growth differences between these two sites at OIRS for juvenile clams cultured in larger protective containers (Barker et al., This Monograph). The major difference appears to result from the effects of depth in reducing the light intensity, especially in these relatively silty conditions. The other point is that there appear to be seasonal or temporal differences in net fouling rates at OIRS. While in winter 1985 similar plastic meshes at the subtidal site were heavily fouled, to the point that there was substantial mortality of the juvenile clams beneath the meshes (unpublished data), during the summer period of this study the untreated meshes recovered from early fouling and were lightly fouled after 3 months of immersion. These temporal differences must result from relative changes in rates of grazing on the fouling organisms (e.g. by grazing fishes) versus rate of growth and recruitment of fouling organisms.

Acknowledgments

This study was part of the Giant Clam Project funded by the Australian Centre for International Agricultural Research (Project 8332). I thank the various project staff and volunteers who assisted with the research, especially Ray Giddins.

Sea Transport of *Tridacna gigas* Broodstock in Solomon Islands

Hugh Govan*

Abstract

The methods used to transport 35 large giant clams, *Tridacna gigas*, to the ICLARM Coastal Aquaculture Center by sea are described. Transport of these clams is feasible over distances of 200 km and probably up to 500 km using small cargo ships and fibreglass tanks filled with seawater. Possible causes for mortality are discussed. A compilation of local names for tridacnid clams in the South Pacific is also included.

In June 1987 broodstock giant clams *Tridacna gigas* were required for the International Center for Living Aquatic Resources Management (ICLARM) Coastal Aquaculture Center (CAC), which is being established on the north/west coast of Guadalcanal, Solomon Islands. No large *T. gigas* had been reported within close range of the CAC, so it was necessary to look to some of the other islands in the archipelago for supplies of broodstock. The nearest reliably reported stocks of *T. gigas* were on the islands of Ysabel and New Georgia more than 200 km away and therefore the collection of broodstock would involve a fairly arduous sea voyage. No record was found in the scientific literature of large clams being transported over long distances by sea, although Beckvar (1981) transported *T. gigas* broodstock for short distances in baitwells filled with seawater in Palau.

The locations chosen for the collection of broodstock, Furona on Ysabel and the Marovo lagoon in New Georgia, were both serviced by small interisland cargo ships of about 400 t gross weight and 40 m in length, which normally transport copra and trochus. The first collection trip took place in June 1987, to Furona, and in the light of results from the first trip, a second one was organised to the Marovo lagoon on a larger scale in July 1987.

Materials and Methods

Potential broodstock *T. gigas* were moved, using a rope sling and sturdy poles, into dugout canoes and then kept in areas of shallow reef to await the arrival of the ship. Clams larger than 65 cm in shell length (SL) generally required three or four people to lift and were difficult to get on board the ship.

The clams were placed in two circular fibreglass tanks (1.85 m in diameter by 0.5 m deep) which were made fast on deck as far aft as possible, close to the ship's superstructure, in order to be near the ship's centre of gravity and thus minimise the effects of the ship's motion on the clams.

The tanks were covered with securely fastened tarpaulins to keep out rainwater, to prevent excessive heating and cooling and to minimise the amount of seawater lost due to spillage during rough weather.

On the first trip the ship's fire pump was relied on to supply fresh seawater whenever required, but due to its frequent failure a 2-inch (5-cm) diesel back-up pump was carried on the second trip enabling very rapid filling of the tanks when the ship was not making way.

On arrival of the ships in Honiara, the nation's capital and the nearest port to the CAC, the broodstock were transferred in the same tanks on a flat-bed truck which was driven slowly out to the CAC (26 km).

Results

First Trip

The voyage from Furona covered 210 km and took 36 hours mainly due to the large number of stops that were made to load cargo. Fourteen clams

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were transported; 6 larger than 65 cm SL and 8 between 40 and 65 cm SL.

Heavy rain was experienced on the voyage and some managed to enter the tanks. For the last 100 km, out of the shelter of Ysabel, force 4–5 winds and moderately rough seas were encountered, which caused the water level in the tanks to fall to around 35 cm.

The ship's fire pump broke down several times but four complete water changes were made in each tank during the course of the voyage. The water temperature inside the tanks stayed between 27.5 and 29.5°C.

On arrival at the CAC one clam was dead, another died within 24 hours and a third clam showed signs of stress but later recovered. All three were larger than 65 cm SL.

Second Trip

The voyage from the Marovo lagoon covered 240 km but only took 18 hours because only one stop was made. Twenty-three clams were transported: 2 larger than 65 cm SL and 21 between 40 and 65 cm SL, although only three of these were smaller than 50 cm SL.

Most of the voyage was across the open ocean and for the first 100 km winds of force 6–8 and extremely rough seas were experienced which caused some damage to the ship and half-emptied the broodstock tanks. However, it did not rain.

The tanks were refilled in the Russell Islands, which was the only time that the water was changed. The water temperature in the tanks stayed between 26.0 and 30.0°C.

On arrival at the CAC only one clam 71 cm SL showed any signs of stress and it recovered within a week.

Discussion

It appears that transport of broodstock *T. gigas* by sea is feasible over distances of at least 240 km and probably up to 500 km as the duration of the voyage appears to be more important than the distance involved.

The mortalities incurred during the first trip probably resulted from the long duration of the trip coupled with the small influx of fresh water during rainstorms.

Clams over 65 cm SL seem to suffer most, probably because they are more susceptible to mechanical stresses due to the ship's motion, particularly when the water level inside the tanks is low, and partly because the larger clams are more difficult to handle and thus receive rougher treatment.

Rough seas do not seem to be a problem provided that the tanks are securely fastened as near to the ship's centre of gravity as possible and tightly covered with tarpaulins to prevent excessive water loss.

Temperature and water quality do not seem to be a problem provided that an autonomous water supply is available occasionally.

The methods used are satisfactory for the transport of clams between 40 and 65 cm SL. The optimum broodstock size for the CAC is probably between 60 and 75 cm SL (Usher and Munro, This Monograph) because of ease of handling and their adequate egg production. Transport of these larger clams could probably be improved by using slightly deeper tanks (e.g. 0.75 m) and improving handling methods.

Acknowledgments

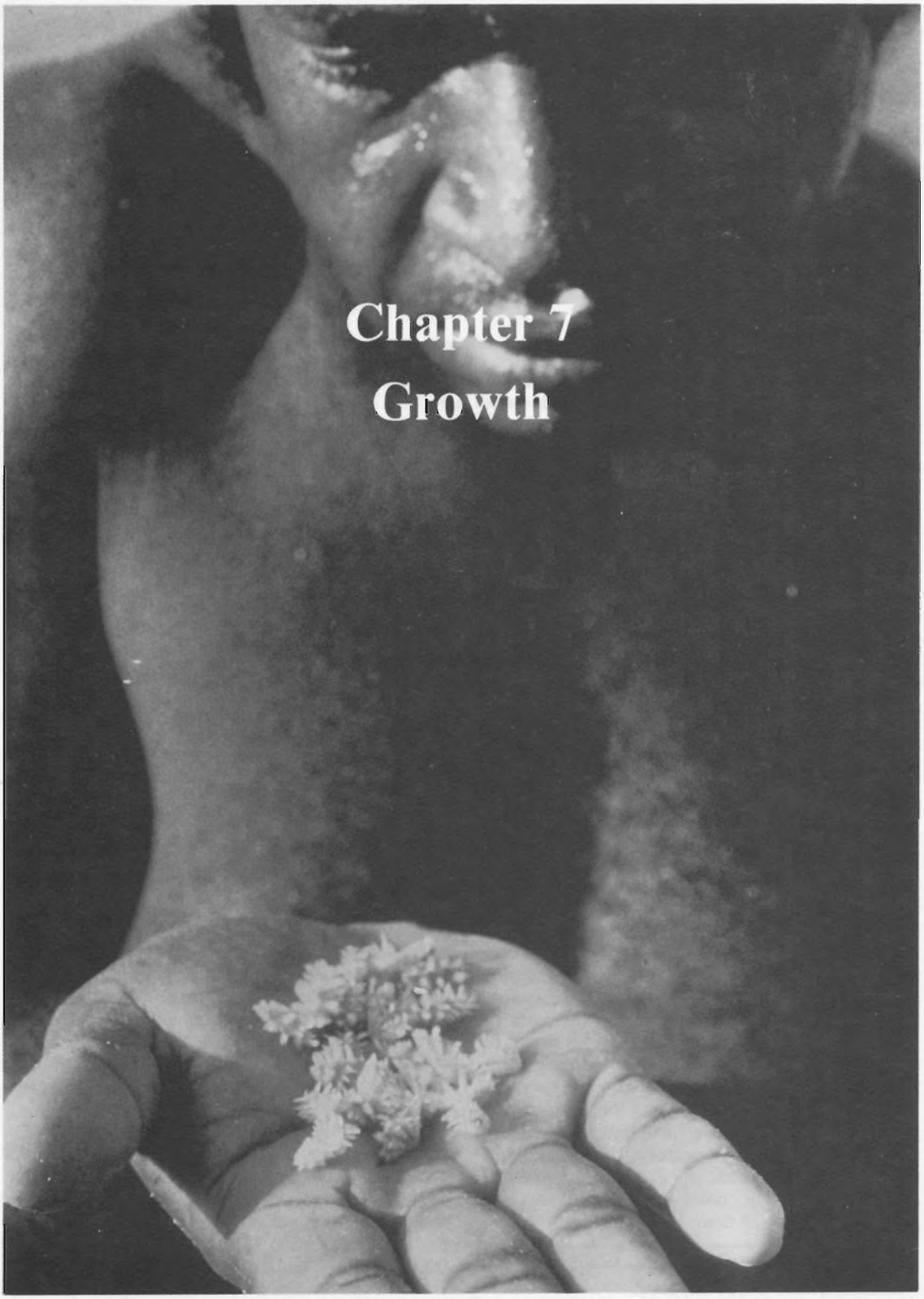
I wish to thank the people of Furona and the Marovo lagoon for their enthusiastic help and support and most of all for their patience.

Appendix

A Compilation of Local Names for Tridacnid Clams in the South Pacific.

Country	Language	*Tridacna gigas*	*Tridacna derasa*	*Tridacna squamosa*	*Tridacna maxima*	*Tridacna crocea*	*Hippopus hippopus*
American Samoa	Samoan	–	–	Faisua	Faisua	–	–
Cook Islands	Cook Islands Maori						
	(Northern group)	–	–	Paua	Paua	–	–
	(Southern group)	–	–	Pa'ua	Pa'ua	–	–
F.S.M.							
Yap							
main island	Yapese	Fasuw (+)	–	Fasuw	Fasuw	Fasuw	Fasuw, Kim
outer island	Woleai (Carolinian)	Hamwe (+)	–	Toh	Toh	Toh	Sum
Pohnpei	Ponapean	Pahsu (+)	–	Sile	Sile	Sile	?
Kosrae	Kosraean	–	Netula	Netula	Netula	Netula	Netula
Kapingamarangi	Kapingamarangian	?	–	Baahua	Baahua	Baahua?	Kima
Truk	Trukese	Amwei (+)	–	To	To	To	Sim
Nukuoroa	Nukuoroan	?	–	Baasua	Baausa	Baasua?	Gima
Fiji	Fijian	Vasua matau (+)	Vasua dina	Cega	Katavatu	–	–
French Polynesia	Polynesian	–	–	–	Pahua	–	–
Guam	Chamorro	–	–	–	Hima	–	–
Kiribati	I-kiribati	Te kima	–	Te were matai	Te were	–	Te nei toro
Marshall Islands	Marshallese	Tangale	—	Mejannoa	Kabajna	–	Dimuj
Nauru	?	?	?	?	?	?	?
New Caledonia	French[1]	–	Bénitier tahitien	Bénitier à ongles	Bénitier à ongles	–	Bénitier rouleur
	e.g. Nenema	–	Fiu	Fiu	Fiu	–	?
Northern Marianas	Chamorro	–	–	–	Hima	–	–
	Carolinian	–	–	–	Toh?	–	–
Palau	Palauan	Otkang	Kism	Ribkungl	Melibs	Orwer	Duadeb
Papua New Guinea	Pidgin[1]	Gramsel	Gramsel	Gramsel	Gramsel	Gramsel	Gramsel
	e.g. Tolai	Korokorot	Korokorot	Korokorot	Korokorot	Korokorot	Korokorot
Solomon Islands	Pijin[1]	Klamsel	Klamsel	Klamsel	Klamsel	Klamsel	Klamsel
	e.g. 'Are'are	Piawa	Sisikeni	Sisimane	Taura	Unupanu	Apuri
	e.g. Ghari	Ghima	–	Inuvitasi	Kapichi	Kapichi	Kwa kwa
Tokelau	Polynesian	–	–	Fahua[2]	Fahua[2]	–	–
Tonga	Tongan	–	Vasua mole mole	Mata hele	Kaku kuku	–	–
Tuvalu	Tuvaluan	Fasua[2]	Fasua?[2]	Fasua[2]	Fasau[2]	–	Fasau[2]
Vanuatu	Bislama[1]	–	Natalai?	Natalai	Natalai	Natalai	Natalai
	e.g. Erakor	–	Kram?	Kram	Kram	Kram	Lisan
Wallis and Futuna	Polynesian	?	–	Fasua?	Fasua?	–	?
Western Samoa	Samoan	–	–	Faisua	Faisua	–	–

– Species not known.
? Name not available or uncertain.
\+ Extinct
[1] The melanesian countries have many local languages (New Caledonia: 28, Papua New Guinea: 600–700, Solomon Islands: 87, and Vanuatu: 115) so only the names in the lingua franca are given and a few examples of local languages.
[2] Large clams are known as 'fahua taka' in Tokelau or 'fasua taka' in Tuvalu.



Chapter 7
Growth

Growth of Giant Clams in Bolinao, Philippines

E.D. Gomez and C.A. Belda*

Abstract

Growth of five species of giant clams (*Tridacna derasa*, *T.gigas*, *Hippopus hippopus*, *T. squamosa* and *T. maxima*) was studied in Bolinao, Pangasinan.

Tridacna derasa juveniles reared in silty water conditions had poor growth and survival but improved remarkably when transferred to relatively clear water. *Hippopus hippopus* juveniles performed the same way but were more tolerant to high sediment load in the water in terms of survival. A second cohort of *H. hippopus* juveniles grew very fast in the field with a growth rate only slightly lower than that of *T. gigas*. This is indicative of the good mariculture potential of this species. *Tridacna gigas* grew in the field three times faster than in the raceway indicating that open water is essential for optimum growth of this species. *Tridacna squamosa* also grew better in the field than in the raceway but with poor survival. *Tridacna maxima* juveniles exhibited good growth and survival in spite of the fact that they were set out in the field at a relatively small size (11.2 mm). Two size-classes of wildstock subadults of the last two species were monitored. Growth rates for the smaller clams (75–100 mm) were slightly greater than those for the larger clams (101–125 mm).

At the start of the ACIAR-supported project the Marine Science Institute was faced with the problem of not having any clams for growth studies.

An initial step taken to resolve the problem was to import *Tridacna derasa* from the Micronesian Mariculture Demonstration Center (MMDC) in Palau. The next sets of juvenile clams for our studies were *T. maxima* and *Hippopus hippopus* that were produced by the Silliman University Marine Laboratory. Wildstock juveniles of *T. squamosa* and *T. maxima* were collected from the reefs of Bolinao, mostly by local fishermen who provided them to us. Fortunately, efforts at inducing some wildstock clams to spawn and rearing the juveniles have been successful such that the majority of juvenile clams for our growth studies are now produced in our own laboratory. These belong to the species *T. squamosa*, *T. maxima* and *H. hippopus*. Presently, however, the most exciting juveniles because of their fast growth are the *T. gigas* that were imported from James Cook University (JCU) of North Queensland.

A number of studies on the growth of giant clams have been undertaken in various countries as reported in the published literature. Noteworthy were the initial efforts at Motupore Island, Papua New Guinea (Munro and Gwyther 1981). Munro and Heslinga (1983) presented a tabulation of available data on the growth of five tridacnid clams (*T. gigas*, *T. derasa*, *H. hippopus*, *T. squamosa* and *T. maxima*). It is interesting to note that the oldest reference they cited was McMichael (1975) on *T. maxima*. Ten years earlier Bonham (1965) had indicated that *T. gigas* was probably the fastest-growing bivalve based on studies of growth rings. Studies in Palau have been of a more recent date in relation to the mariculture efforts there. To complement the tabulation of Munro and Heslinga mentioned above, the growth rates of *T. crocea* are provided by Hamner and Jones (1976) who note an initial 2.0 cm for the first year, 1.5 cm for each of the next 2 years, and a rapid decline thereafter. This is similar to Murakoshi's (1986) finding that juvenile

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T. crocea grew from 0.48 to 6.61 cm in 4 years, that is, approximately 1.5 cm/year. Data on the growth of the seventh species, the China clam *H. porcellanus*, are yet to be published since the studies were initiated only recently at Silliman University where this species was first successfully induced to spawn (Alcazar et al. 1987).

Materials and Methods

As indicated earlier, the clams for the growth studies at the Marine Science Institute have come from various sources. Imported clams were routinely quarantined for 6 months according to the agreed protocol of the project. This was done at the Bolinao Marine Laboratory of the Institute. Following quarantine, the clams were treated in the same way as local clams.

In the raceway, clams were maintained in a seawater system with running seawater during the day. At night, the flow was stopped. Mean daytime temperature of the raceways ranged from 26.7 to 30.2°C. Water depth averaged 0.7 m.

Initial field sites were on opposite sides of the channel between Santiago Island and the mainland, that is, in Tomasa and Guiguiwanen (Fig. 1). The water was not very clear in the channel. The experimental sites had depths of 4–5 m.

Currently, all field growth studies are carried out in the ocean nursery north of Silaqui Islet on the extensive reef flat north of Santiago Island (Fig. 1). The water here is clear and the depth is about 3 m. The juvenile clams are mostly raised in bamboo cages about 0.6 m above the seagrass/sand substrate. Measurements were done at intervals of 1 month or longer.

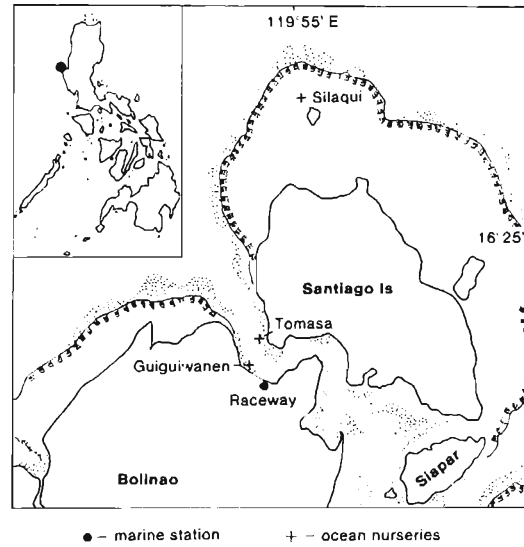

Fig. 1. The study sites in Bolinao, Philippines.

Results

Source and other data concerning the experimental animals are presented in Table 1. Table

TABLE 1. Giant clams used in growth studies.

Species	Source	Spawning date	Age upon arrival/start of experiment	Quarantine period
A. Cultured clams				
T. derasa	Palau	3/84	9 months (N = 293)	12/84–3/85 (4 months)
T. gigas	JCU	10/85	14 months (N = 328)	2/87–7/87 (5 months)
H. hippopus	SU	8/85	10 months (N = 95)	7/86–10/86 (4 months)
	MSI	2/87	6½ months (N = 200)	-
T. squamosa	MSI	6/86	4 months (N = 200)	-
T. maxima	MSI	2/87	6½ months (N = 200)	-
B. Wildstock clams				
Subadult *T. maxima* and *T. squamosa* were collected from the reefs around Bolinao, Pangasinan at various times over the past several years. These were tagged and measured periodically in the nursery. Although there are now some 61 *T. maxima* and 96 *T. squamosa*, a smaller number was included in this paper, representing those held in the nursery for the longest period.				

JCU, James Cook University; MSI, Marine Science Institute; SU, Silliman University.

2 contains a summary of the growth of various cohorts of giant clams. Survival data were tabulated for all the cultured clams (Table 3). The survival rates of the wildstock clams, however, were not included in the table in as much as the clams comprising this group were acquired at various times. Finally, some environmental parameters measured at the study sites are presented in Table 4.

Discussion

The *T. derasa* juveniles reared in Tomasa grew more slowly than those in Guiguiwanen with growth rates of 1.8 and 2.4 mm/month, respectively. Survival was likewise lower in the former (7%) than in the latter (14%). These differences in growth and survival of the clams correlated with and may be attributed to the higher sedimentation rate in Tomasa (4.20 g/cm^2/month) compared with Guiguiwanen (2.4 g/cm^2/month). Upon transfer to Silaqui, growth rates picked up for both cohorts to 3.3 and 3.6 mm/month, respectively. Survival likewise remarkably improved and is now maintained at 100% for both cohorts. This improvement is attributed to the relatively clear water in Silaqui with an average sedimentation rate of only 0.15 g/cm^2/month. The improved growth rates of *T. derasa* are close to the MMDC's

TABLE 2. Summary of growth of giant clams in the raceway and ocean-based nurseries.

Species	Spawning date	Nursery site	Duration in nursery	Initial mean length (mm)	Final mean length (mm)	Total length increment (mm)	Growth rate (mm/mo)
A. Cultured clams							
T. derasa	3/84	Tomasa	4/6/85–18/10/86 (502 days)	64.5	94.2	29.7	1.8
		Guiguiwanen	4/6/85–18/10/86 (502 days)	60.9	100.5	39.6	2.4
		Tomasa to Silaqui	18/10/86–16/2/88 (486 days)	94.2	147.1	52.9	3.3
		Guiguiwanen to Silaqui	18/10/86–16/2/88 (486 days)	100.5	158.9	58.4	3.6
T. gigas	10/85	Raceway	13/7/87–16/2/88 (218 days)	76.6	90.8	14.2	2.0
		Silaqui	13/7/87–16/2/88 (218 days)	75.6	126.4	50.8	7.0
H. hippopus	8/85	Raceway	29/10/86–19/12/87 (416 days)	56.9	81.9	25.0	1.8
		Silaqui	29/10/86–19/12/87 (416 days)	59.5	99.3	39.8	2.9
		Tomasa	29/10/86–18/2/87 (112 days)	60.0	61.8	1.8	0.5
		Tomasa to Silaqui	18/2/87–19/12/87 (304 days)	61.8	84.1	22.3	2.2
	2/87	Raceway	11/8/87–15/1/88 (157 days)	15.7	38.3	22.6	4.3
		Silaqui	11/8/87–15/1/88 (157 days)	15.9	49.6	33.7	6.4
T. squamosa	6/86	Raceway	29/10/86–15/6/87 (259 days)	12.2	21.4	9.2	1.1
		Silaqui	29/10/86–17/2/88 (476 days)	12.7	48.8	36.1	2.3
T. maxima	2/87	Raceway	11/8/87–15/1/88 (157 days)	11.2	22.0	10.8	2.1
		Silaqui	11/8/87–15/1/88 (157 days)	10.2	23.7	13.5	2.6
B. Wildstock clams	Size class (mm)						
T. squamosa	75–100	Silaqui	2/87–3/88	90.6	120.6	30.0	2.1
	101–125		(420 days)	115.6	142.1	26.5	1.9
T. maxima	75–100	Silaqui	2/87–3/88	91.6	114.9	23.3	1.7
	101–125		(420 days)	113.0	132.1	19.1	1.4

projected growth of 3.8 mm/month (Beckvar 1981). These findings indicate that relatively sediment-free water is essential for good growth and survival of *T. derasa*.

The *T. gigas* juveniles in Silaqui grew more than three times (7.0 mm/month) the rate of the raceway cohort (2.0 mm/month) with the same survival rate of 99%. Open water seems to be a prerequisite for good growth of this species. The growth rate in Silaqui is lower but not far from the value obtained in a benthic subtidal site in Pioneer Bay (7.9 mm/month) by the JCU group (ACIAR 1986) and the projected growth rate for this species at 8.3 mm/month (Beckvar 1981). Our lower value may be attributed to the fact that the clams suffered from severe bleaching during quarantine which may

TABLE 3. Summary of survival of giant clams in the land- and ocean-based nurseries.

Species	Spawning date	Nursery site	Duration in nursery	Initial number	Final number	Survival %
T. derasa	3/84	Tomasa	4/6/85–18/10/86 (502 days)	243	18	7.4
		Guiguiwanen	4/6/85–18/10/86 (502 days)	50	7	14.0
		Tomasa to Silaqui	18/10/86–16/2/88 (486 days)	18	18	100.0
		Guiguiwanen to Silaqui	18/10/86–16/2/88 (486 days)	7	7	100.0
T. gigas	10/85	Raceway	13/7/87–16/2/88 (218 days)	83	82	98.8
		Silaqui	13/7/87–16/2/88 (218 days)	85	84	98.8
H. hippopus	8/85	Raceway	29/10/86–19/12/87 (416 days)	34	32	94.1
		Silaqui	29/10/86–19/12/87 (416 days)	31	29	93.5
		Tomasa	29/10/86–18/2/87 (112 days)	30	21	70.0
		Tomasa to Silaqui	18/2/87–19/12/87 (304 days)	21	20	95.2
	2/87	Raceway	11/8/87–15/1/88 (157 days)	100	92	92.0
		Silaqui	11/8/87–15/1/88 (157 days)	100	99	99.0
T. squamosa	6/86	Raceway	29/10/86–15/6/87 (259 days)	100	43	43.0
		Silaqui	29/10/86–17/2/88 (476 days)	100	10	10.0
T. maxima	2/87	Raceway	11/8/87–15/1/88 (157 days)	100	67	67.0
		Silaqui	11/8/87–15/1/88 (157 days)	100	92	92.0

TABLE 4. Environmental parameters measured in the different study sites.

	Temperature (°C)		Salinity (ppt)		Light intensity ($\mu E/m^2/sec$)			Sedimentation ($g/cm^2/mo$)		
Study site	Range	Mean	Range	Mean	Atm	OC	IC	Range	Mean	Period covered
Tomasa	28.0–30.8	29.4	31.0–35.0	33.5	1400	300	165	0–24.60	4.20	23/2/85–16/10/86
Guiguiwanen	–	–	29.0–33.0	31.0	–	–	–	0–15.00	2.40	23/2/85–16/10/86
Silaqui	28.0–33.8	30.1	32.0–36.0	33.7	2323[b] 643[c]	1196[b] 287[a]	1189[b] 124[c]	0–0.24	0.15	1/87–12/87
Raceway	26.7–30.2	28.7	33.4–37.0	35.8	2488 1876[d]	1350	–	–	–	–

[a] Atm — atmospheric reading; OC — underwater outside cage; IC — underwater inside cage. [b] Clear sky; [c] cloudy sky; [d] under net cover.

have hampered their growth. They are expected to further improve as they have been in Silaqui for only 8 months.

The *H. hippopus* (batch 8/85) reared in Tomasa were stunted exhibiting a growth rate of only 0.5 mm/month with a survival rate of 70%. Upon transfer to Silaqui, they caught up with their raceway siblings. These cohorts exhibited growth rates of 2.2 and 1.8 mm/month, respectively. On the other hand, the growth rate of the clams in Silaqui (2.9 mm/month) was only slightly less than the projected 3.3 mm/month growth rate for this species (Beckvar 1981). It seems that *H. hippopus* was more tolerant of the silty conditions in Tomasa than was *T. derasa* as reflected in its higher survival.

It is interesting to note that the *H. hippopus* (batch 2/87) juveniles fared well in the ocean nursery. Their growth rate (6.4 mm/month) is about twice their projected growth rate of 3.3 mm/month as mentioned above. The growth rate of the raceway cohort (4.3 mm/month), although lower than the Silaqui cohort, still exceeds the projected growth rate for this species. This seems to be a very good batch as its growth rate approaches that of *T. gigas*. This indicates that, aside from *T. gigas*, *H. hippopus* could be another good candidate for mariculture.

The *T. squamosa* juveniles reared in Silaqui grew twice as fast as those in the raceway with growth rates of 2.3 and 1.1 mm/month, respectively. The growth rate of the Silaqui cohort is considerably less than that of the *T. squamosa* reared by the University of Papua New Guinea (UPNG) group which had a growth rate of 6.0 mm/month (ACIAR 1986). Furthermore, survival of this species was low at 43% for the raceway cohort after 259 days and 10% for the Silaqui cohort after 476 days. This very low survival cannot be explained at this point and needs further investigation.

The *T. maxima* juveniles reared in Silaqui grew faster than those reared in the raceway exhibiting growth rates of 2.6 and 2.1 mm/month, respectively. The Silaqui cohort also had a high survival rate of 92%. This is interesting since the juveniles were put out in the field at a relatively small mean size of 11.2 mm. This demonstrates that *T. maxima* can be transplanted early in the field so long as they are provided with a suitable substrate where they can firmly attach. In our case, we provided them with coral rubble.

The wildstock clams belonging to the 75–100-mm size-class exhibited slightly greater growth rates (2.1 mm/month for *T. squamosa* and 1.7 mm/month for *T. maxima*) compared with those in the 101–125-mm size-class (1.9 mm/month for *T. squamosa* and 1.4 mm/month for *T. maxima*).

The above results are a subset of the studies undertaken in the project. The results of other experiments will be published elsewhere.

Acknowledgments

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Growth and Mortality of Juvenile Giant Clams (*Tridacna gigas*) in Relation to Tidal Emersion on a Reef Flat

W.J. Nash*

Abstract

Growth and mortality rates of juvenile *Tridacna gigas* were investigated in relation to tidal elevation in Pioneer Bay, Orpheus Island, North Queensland. Clams were placed on adjacent platforms at five different elevations: 0, 50, 80, 105 and 120 cm above tidal datum respectively. Both 1+ and 2+ year-classes were used, with two trays of each age-class/level and 20 clams/tray. The experiment ran from October 1986 to August 1987. Shell lengths were measured at approximately 2-month intervals.

For the 1+ clams, mortality was very low or zero at the lowest three levels, and total at the highest two levels. The 2+ clams experienced very low or zero mortality at all five levels, except for one tray at the middle level (80 cm above datum), where mortality was 70%, and one tray at the second highest level (105 cm above datum), which was lost in rough weather.

Growth of the 1+ clams was similar at all three levels at which they survived. Growth of the 2+ clams at the lowest three levels was also similar, but was much faster than at the highest two levels. It was concluded that there is an emersion threshold somewhere between those found at elevations 3 and 4 — that is, between 3.75 and 6.4 hours mean daily emersion — beyond which growth slows greatly. Combining the results of this experiment with others from James Cook University this threshold lies between 5.0 and 6.4 hours total daily emersion.

An analysis of growth rates in relation to water temperature and mean daily emersion indicated that at low levels of emersion ($\leq$3.75hours/day), growth rate is positively correlated with temperature, while at higher emersion levels, growth and temperature are negatively correlated, presumably because emersion is more stressful at higher temperatures.

In a comparison of growth and survival of juvenile *Tridacna gigas* in four ocean-nursery culture methods, Crawford et al. (1988) found that high levels of growth and survival were attained in the low intertidal zone. In a subsequent study to determine the level of aerial exposure this species could tolerate, it was found that there is a threshold somewhere between 5 and 10 hours average daily exposure at which growth is greatly retarded (Lucas et al. in prep.). In the latter study, different elevations of the clam cages in relation to tide height were achieved by placing the cages across the very wide, gently sloping intertidal reef flat in Pioneer Bay, Orpheus Island, on the Great Barrier Reef. The lowest and highest cages were some 300 m apart.

The present study is an extension of that described by Lucas et al. (in prep.) and was designed to determine more precisely the level of exposure *T. gigas* can tolerate without suffering significant retardation of growth or increase in mortality. In addition, since the clams in the study of Lucas et al. (in prep.) were spread over a wide area of reef flat, it was possible, though not likely, that the observed

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differences in growth rate were site-related, not tidal height-related. This possibility was precluded in the present study by placing all experimental clam cages at a single site. Growth patterns were consistent with those found in the previous study (Lucas et al. in prep.).

Methods

The experiment was situated at the northern end of Pioneer Bay, Orpheus Island, in the vicinity of other giant clam experiments. The site was chosen because of its sheltered position from all but northerly and northwesterly swells, as well as its remoteness from tourist traffic to and from the research station. The area was near the outer edge of the reef flat, where microatolls of the massive hard coral *Porites lutea* predominated. Substrate was otherwise bare or alga-covered coral rock, or other robust growth forms of hard corals.

The standard experimental unit was the same as that of Crawford et al. (1988) and Lucas et al. (in prep.): a perforated plastic tray, 550 × 300 × 90 mm. Four trays were placed on each level of a structure resembling a staircase of five levels. The structure consisted of sheets of 100 × 60 mm galvanised steel mesh wired in a horizontal position to steel pegs driven vertically into the substrate. The trays were secured to these mesh bases, four trays/level, and a layer of 15–20 mm sized road gravel (crushed basalt) added. Each tray was covered with a removable 26 mm plastic mesh lid. Twenty juvenile *T. gigas* were placed in each tray. Two trays of each set of four contained *T. gigas* spawned in February 1985 (hereafter called 2+ clams), and two contained *T. gigas* spawned in October 1985 (1+ clams). Thus, there were 80 clams on each of the five levels for a total of 400 clams.

The five levels (levels 1 to 5 respectively) were at 0, 50, 80, 105 and 120 cm above datum for Lucinda, the nearest port for which tidal information was available. Chart datum for Lucinda was indicated at the southern point of Pioneer Bay from a previous study (Parnell 1986).

Using the tidal information, it was possible to calculate the duration of emersion of the clams at each level of the staircase, using a computer program in MBASIC prepared by Dr J.D. Collins. Emersion time was calculated as a proportion of the total time, for the entire period between measurements. Emersion time was also calculated as a proportion of daytime (6 am to 6 pm) and proportion of nighttime (6 pm to 6 am).

Water temperature was recorded continuously in the research station seawater system. The daily temperature range in this system may have been slightly greater than in the adjacent bay, due to the influence of land temperature; the median daily temperature was therefore used as the representative daily water temperature.

All clams were drained by inverting them for about 10 min, weighed to 0.01 g, and maximum shell length measured to 0.1 mm. The 200 clams in each age-class were divided between 10 trays such that the means and standard deviations of their lengths were approximately equal. This was done to facilitate subsequent statistical analysis. The clams were individually labelled with a numbered plastic strip glued with epoxy resin to the shell after cleaning and drying an area of the shell to minimise the chance of tag loss.

The experiment was commenced on 29 October 1986, and terminated ten months later on 26 August 1987. Lengths of all clams were measured at approximately 2-month intervals. Measurement dates were as follows: in 1986, 29 October and 26 December; and in 1987, 18 February, 15 April, 5 June and 26 August.

Frequent reference is made throughout the text to the intervals between these dates. These are as follows: Interval 1: 29 October to 26 December 1986; Interval 2: 26 December 1986 to 18 February 1987; Interval 3: 18 February to 15 April; Interval 4: 15 April to 5 June; and Interval 5: 5 June to 26 August. The clams were inspected approximately every 2 weeks. Scrubbing of the lids to remove fouling algae was generally not necessary, as found earlier (Crawford et al. 1988). At the conclusion of the experiment, all surviving clams were reweighed and a final measurement of shell lengths and weights made.

Growth variation was analysed in two ways: firstly, by a comparison of the length measurements; and secondly, by comparing relative growth rates, expressed as the percentage change in length between two successive measurements, and standardised as the incremental increase for a 28-day period:

$$G_R = 100 \times ((L_{t+1} - L_t)/L_t) \times 28/\Delta t,$$

where G_R is relative growth rate, L_t and L_{t+1} are length measurements at successive times t and $t+1$, and Δt is the time interval (in days) between these measurements. Since G_R is a measure of relative growth, changes in water temperature or daily emersion times between measurement periods will be more closely reflected in G_R than in the length increments alone, which will also be dependent on the size at the previous measurement.

Results

At the second remeasurement (4 months after the experiment began), it was apparent that the 2+ clams had grown to a size at which overcrowding was occurring. Clams were removed at random with respect to size until there were 10/tray. This was

TABLE 1. Survival rates (%) of juvenile *Tridacna gigas* during the course of the experiment, for 1+ and 2+ clams, shown for each tray at each level.

	Tray level									
	Level 1		Level 2		Level 3		Level 4		Level 5	
	Tray 1	Tray 2	Tray 1	Tray 2	Tray 1	Tray 2	Tray 1	Tray 2	Tray 1	Tray 2
1+ clams	95	100	100	85	95	90	0	0	0	0
2+ clams	100	100	95	95	95	30	85	–[a]	100	95

[a] Lid washed off and clams lost, presumably through wave action and/or predation.

done because it has been found that overcrowding induces shell deformation and inhibits linear growth (unpublished observations).

Mortality

Between the start of the experiment and the first remeasurement 2 months later, all 1+ clams in the two most elevated levels (levels 4 and 5) were dead. They were unable to survive the stressful conditions. Some time between the first and second remeasurements, one tray on the second highest level (level 4) was lost, presumably through wave action.

Survival rates of clams at each level are summarised in Table 1. The loss of a tray from level 4 was not treated as part of this, because it was not caused by the emersion factors that this experiment was trying to assess. In most cases, the two trays containing clams of the same age at each level experienced similar survival rates. Exceptions to this were the 2+ clams at level 3, where one tray experienced substantial losses, whereas the other did not (Table 1). Similarly, there was substantial mortality in one tray of 2+ clams at level 4 at the first remeasurement. There is no record of these losses at the time of remeasurement, so no explanation for the high mortalities can be offered.

Growth

For both the 1+ and 2+ clams, the growth rates at the lowest three levels (levels 1–3) are very similar within age-groups (Fig. 1,2). Similarly, growth rates of 2+ clams at levels 4 and 5 are similar. The difference in growth rates of 2+ clams between levels 1–3 and levels 4–5, however, is great (Fig. 1). Clams at 105 and 120 cm above datum (levels 4 and 5) grew much more slowly than those at or below 80 cm above datum (levels 1–3). Thus, the threshold above which there is a substantial decrease in growth rate by juvenile *T. gigas* lies between 80 and 105 cm above chart datum — that is, between 3.75 and 6.4 hours mean total daily emersion.

At levels 4 and 5, mean sizes of the 2+ clams actually decreased between the start of the experiment and the first remeasurement (Fig. 2). It is noteworthy that at the end of the experiment the 1+ clams from levels 1–3 had grown much more rapidly than the 2+ clams from levels 4 and 5 and were almost the same shell length (Fig. 1, 2).

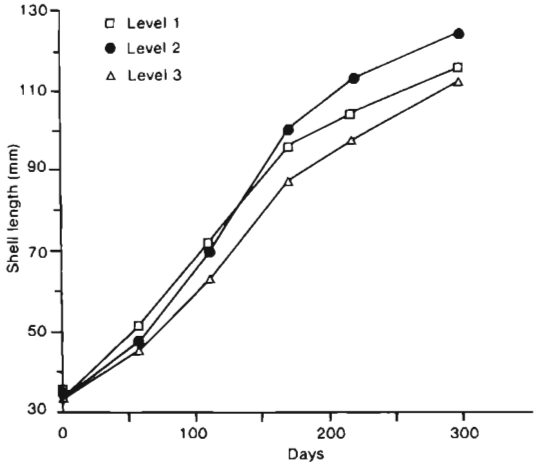

Fig. 1. Growth of 1+ *Tridacna gigas* at emersion levels 1–3 between October 1986 and August 1987.

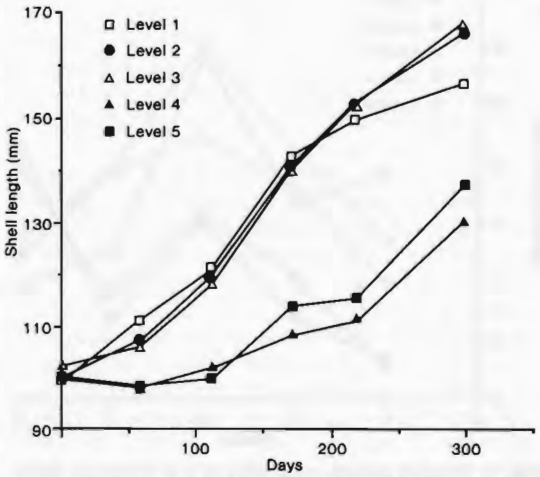

Fig. 2. Growth of 2+ *Tridacna gigas* at five emersion levels between October 1986 and August 1987.

When expressed in terms of relative growth rate G_R, the distinction between the lower three levels and the upper two for each age-class is less clear (Fig. 3, 4). At all five levels, the 2+ clams followed similar trends until the final measurement, when relative growth at levels 4 and 5 was faster than at levels 1-3 (Fig. 4).

Since the two factors most likely to be determining growth rates are temperature and duration of emersion, the relationship between growth rate and each of these was then examined. The relationship between growth rate G_R and duration of exposure is shown in Fig. 5 for both 1+ and 2+ clams. Exposure is expressed firstly as mean total exposure, then broken down into daytime and nighttime components. Least squares regression lines are fitted for each level of exposure. None of these lines has a slope significantly different from zero except for levels 2 and 3 (daytime exposure) for the 1+ clams, and level 1 (nighttime exposure) for the 1+ clams. However, some trends are apparent, most importantly among the 2+ clams. There is a marked difference in growth pattern between levels 1-3 and levels 4-5 (Fig. 5D). At levels 4 and 5, there is a positive correlation between daytime exposure and growth rate, and a negative correlation between nighttime exposure and growth rate (Fig. 5E, F).

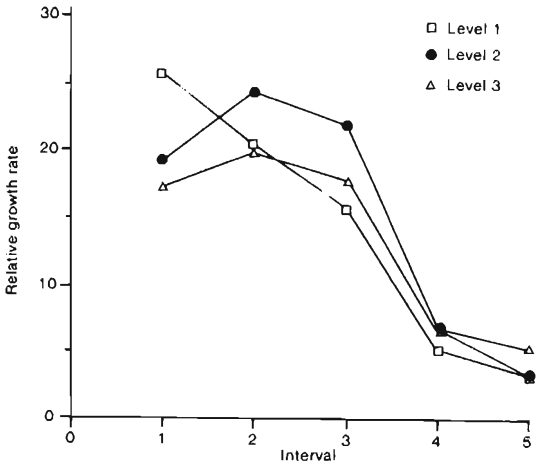

Fig. 3. Relative growth rates (G_R) of 1+ *Tridacna gigas* at emersion levels 1-3 between October 1986 and August 1987.

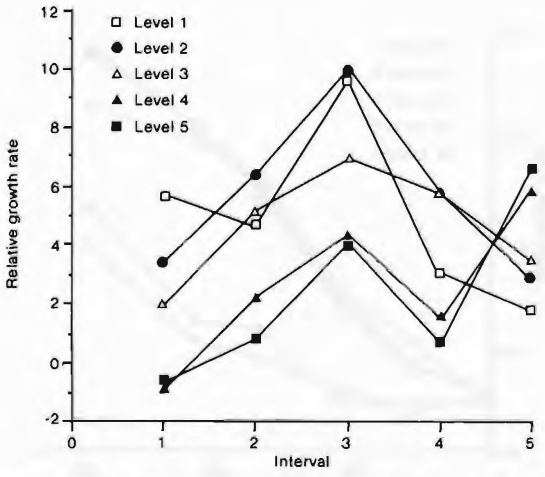

Fig. 4. Relative growth rates (G_R) of 2+ *Tridacna gigas* at five levels of emersion between October 1986 and August 1987.

This may be attributed to the fact that daytime emersion is longest in winter and shortest in summer; conversely, nighttime emersion is longest in summer and shortest in winter This is shown in Fig. 6, which is for level 4. Daytime and nighttime emersion are of approximately equal duration between February and April (interval 3· Fig. 6). Hence, faster growth at higher daytime emersion levels may simply reflect the fact that temperatures are lowest when daytime emersion is longest (i.e. in winter), and that at high levels of emersion, high temperatures are stressful.

The relationship between growth rate and temperature at each exposure level was then examined. This relationship is particularly close for the 1+ clams (Fig. 7). A similar but less close relationship exists at levels 1-3 for the 2+ clams. The pattern at levels 4 and 5 is less clear, but the largest increase in growth rate occurred towards the end of the experiment when temperatures were at their lowest.

The relative growth rates (G_R) overall, between the start and end of the experiment 10 months later, were then compared. Analysis was by two-way nested analysis of variance (ANOVA), comparing G_R between levels and between trays at each level, with clams replicated within each tray. For the 2+ clams, level 4 had to be excluded because of the absence of one tray. Levels 4 and 5 were excluded from the analysis of the 1+ clams because all clams at these levels died shortly after the experiment began.

Relative growths of the 1+ and 2+ clams were not analysed in a single ANOVA design because of the different missing value patterns — particularly, among the 2+ clams, one tray was missing from level 4, and all trays at levels 4 and 5 were missing for the 1+ clams. The differences in relative growth between the start and end of the experiment between 1+ and 2+ clams are great, however (Fig. 3,4), ranging from 14.98 to 38.51 for 1+ clams and 1.11 to 8.36 for 2+ clams.

For the 2+ clams relative growth differed

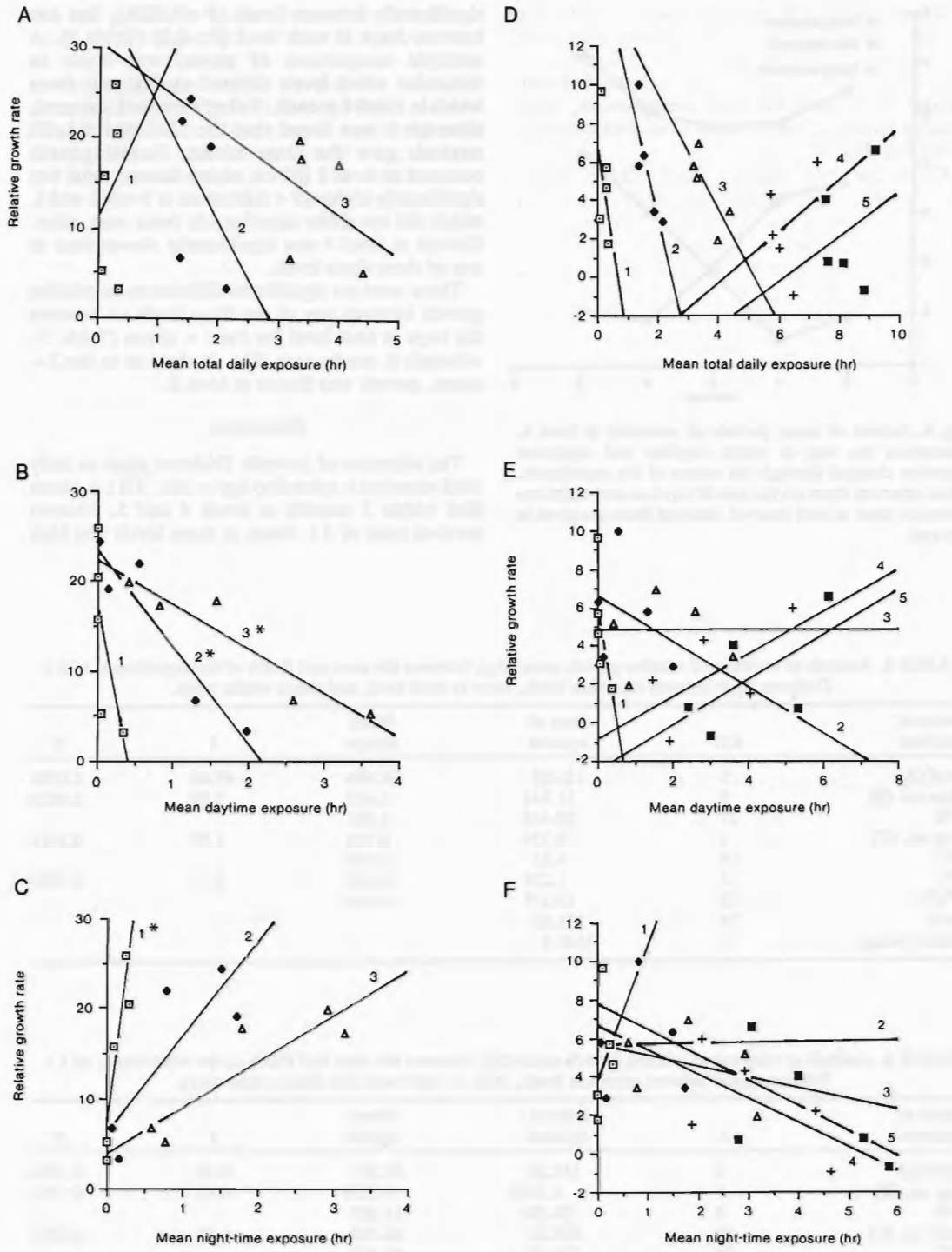

Fig. 5. Relationship between relative growth rate and mean periods of emersion at different elevations for 1+ (A-C) and 2+ (D-F) *Tridacna gigas*, expressesd per 24 hours (A,D), per 12 hours of night (B,E) and per 12 hours of daylight (C,F). □ level 1; ● level 2; △ level 3; + level 4; ■ level 5. Regression lines marked with an asterisk had slopes significantly different from zero ($P < 0.05$). Numbers on lines signify level of elevation.

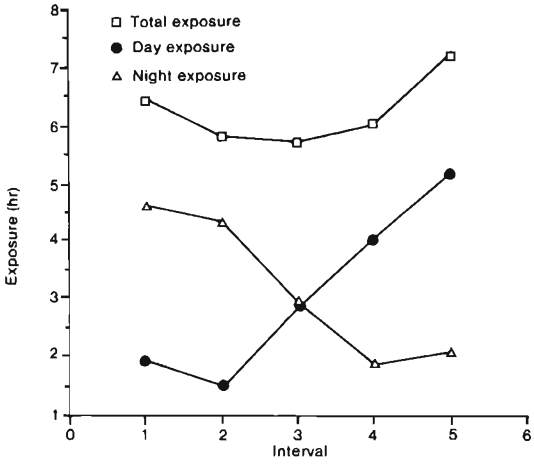

Fig. 6. Pattern of mean periods of emersion at level 4, illustrating the way in which daytime and nighttime emersion changed through the course of the experiment. Total emersion times are the sum of daytime and nighttime emersion times at each interval. Interval dates are given in the text.

significantly between levels ($P<0.0001$), but not between trays at each level ($P>0.2$) (Table 2). A multiple comparison of means was made to determine which levels differed significantly from which in relative growth. Tukey's method was used, although it was found that the LSD and Scheffé methods gave the same results. Fastest growth occurred at level 2 (50 cm above datum), and was significantly higher ($P<0.05$) than at levels 1 and 3, which did not differ significantly from each other. Growth at level 5 was significantly slower than at any of these three levels.

There were no significant differences in relative growth between any of the three levels or between the trays at each level for the 1+ clams (Table 3), although it can be seen (Fig. 1) that, as in the 2+ clams, growth was fastest at level 2.

Discussion

The tolerance of juvenile *Tridacna gigas* to daily tidal emersion is related to age or size. All 1+ clams died within 2 months at levels 4 and 5, whereas survival rates of 2+ clams at these levels was high

TABLE 2. Analysis of variance of relative growth rates (G_R), between the start and finish of the experiment, of 2+ *Tridacna gigas* between emersion levels, trays at each level, and clams within trays.

Source of variation	d.f.	Sum of squares	Mean square	F	P
Level (A)	3	155.09	51.696	47.40	0.0000
Clam no. (B)	9	21.841	2.427	2.23	0.0523
A*B	27	29.445	1.091		
Tray no. (C)	1	0.736	0.736	1.57	0.2413
B*C	9	4.21	0.468		
A*C	3	1.228	0.409	0.47	0.7093
A*B*C	22	19.347	0.879		
Total	74	231.89			
Grand average	1	2148.2			

TABLE 3. Analysis of variance of relative growth rates (G_R), between the start and finish of the experiment, of 1+ *Tridacna gigas* between emersion levels, trays at each level and clams within trays.

Source of variation	d.f.	Sum of squares	Mean square	F	P
Level (A)	2	134.50	67.251	6.02	0.1424
Tray no. (B)	1	1.2118	1.2118	0.11	0.7731
A*B	2	22.333	11.167		
Clam no. (C)	19	820.24	43.170	2.19	0.0480
B*C	19	374.66	19.719		
A*B*C	66	551.43	8.355		
Total	109	1 904.4			
Grand average	1	62 709			

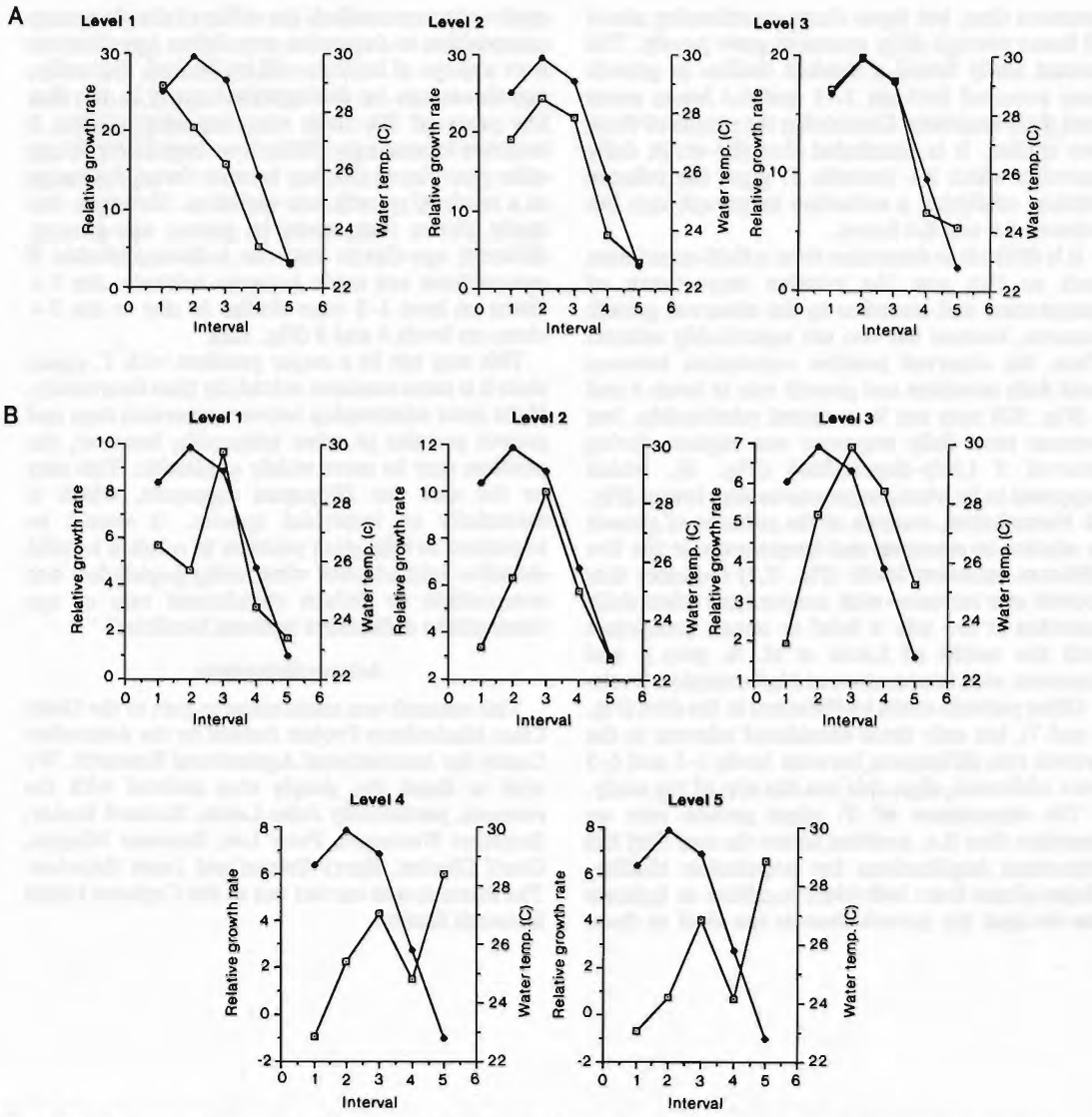

Fig. 7. Relative growth rates of (A) 1+ and (B) 2+ *Tridacna gigas* in relation to water temperature at the different levels of emersion. ⊡ relative growth; • water temperature (°C). Interval dates are given in the text.

(Table 1). Physiological homeostasis is more easily maintained as body size increases, because of increasing volume:surface area ratio. Smaller animals therefore are less able to withstand the heating and desiccating effects of prolonged exposure to the air. Despite high survival by the 2+ clams at levels 4 and 5, the retarded growth rates there indicate that the conditions were still stressful.

Growth rates of *T. gigas* were similar at levels 1–3 (Fig. 1,2) and declined markedly at levels 4 and 5). There is no evidence of a gradual decline in growth rate as emersion time increased and this raises the possibility that the level at which growth slows is an abrupt threshold, above which growth (and probably other metabolic processes) rapidly declines.

In an earlier study, Crawford et al. (1988) showed that growth of juvenile *T. gigas* in the low intertidal zone is comparable with that in shallow subtidal localities. Lucas et al. (in prep.) examined the emersion tolerances of *T. gigas* across the reef flat in Pioneer Bay, Orpheus Island, and showed that high growth rates were achieved up to a level corresponding to about 5 hours average daily

emersion time, but those clams experiencing about 10 hours average daily emersion grew poorly. The present study found a marked decline in growth rates occurred between 3.75 and 6.4 hours mean total daily emersion. Combining the results of these two studies, it is concluded that the mean daily emersion which 2+ juvenile *T. gigas* can tolerate without exhibiting a reduction in growth rate lies between 5.0 and 6.4 hours.

It is difficult to determine from a field experiment such as this one the relative importance of temperature and emersion to the observed growth patterns, because the two are inextricably related. Thus, the observed positive correlation between total daily emersion and growth rate at levels 4 and 5 (Fig. 5D) may not be a causal relationship, but because total daily exposure was highest during interval 5 (July–September) (Fig. 6), which happened to be when temperatures were lowest (Fig. 7). Nevertheless, analysis of the patterns of growth in relation to emersion and temperature at the five different emersion levels (Fig. 5,7) indicates that growth rate increases with temperature when daily emersion at low tide is brief or absent (consistent with the results of Lucas et al. in prep.), and decreases with temperature at high emersion levels.

Other patterns could be discerned in the data (Fig. 5 and 7), but only those considered relevant to the growth rate differences between levels 1–3 and 4–5 were addressed, since this was the aim of the study.

The dependence of *T. gigas* growth rate on emersion time (i.e. position across the reef flat) has important implications for population studies. Unless clams from individual localities or habitats can be aged (by growth lines in the shell or from mark-recapture studies), the utility of size-frequency composition to determine population age structure over a range of habitats will be limited. Generally, age-classes can be distinguished easily in the first few years of life from size-frequency modes; it becomes increasingly difficult or impossible to age older year-classes this way because the modes merge as a result of growth rate variation. However, this study shows that, even in young age-groups, different age-classes may be indistinguishable if comparisons are made between habitats: the 1+ clams on level 1–3 were similar in size to the 2+ clams on levels 4 and 5 (Fig. 1,2).

This may not be a major problem with *T. gigas*, since it is more common subtidally than intertidally. If the same relationship between emersion time and growth pertains to other tridacnids, however, the problem may be more widely applicable. This may be the case for *Hippopus hippopus*, which is essentially an intertidal species. It would be important to take clam position in relation to tidal elevation into account when using population size composition to deduce recruitment rate or age composition differences between localities.

Acknowledgments

This research was undertaken as part of the Giant Clam Mariculture Project funded by the Australian Centre for International Agricultural Research. We wish to thank the people who assisted with the research, particularly John Lucas, Richard Braley, Stephane Westmore, Peter Lee, Suzanne Mingoa, Geoff Charles, Harry Brown and Janet Estacion. The research was carried out at the Orpheus Island Research Station.

Growth and Survival of *Tridacna gigas* Juveniles in an Intertidal Pond

Janet S. Estacion* and Richard D. Braley**

Abstract

Several methods for rearing giant clams in the sea have been investigated. Clams were placed in trays, cages and lines in several positions: intertidal, subtidal and floating. This experiment was conducted to determine the possibility of rearing juvenile clams high in the intertidal zone using ponds. Although ponding was favourable to survival, growth was slow, possibly due to increased water temperature and decreased nutrients.

JUVENILE *Tridacna gigas* (9.5 and 18.5 months old) were individually measured, weighed, tagged and placed in trays in two rectangular fibreglass tanks (2.5 m long × 0.8 m wide × 0.4 m high). Eighty clams of each age class were used, being placed 20/tray in four trays. The fibreglass tanks were fixed to the substrate 2 m above datum point (tidal range -0.34 to 3.59 m) and sited at the foot of the beach slope in Pioneer Bay, Orpheus Island, Great Barrier Reef, behind a clump of mangroves for protection.

No protective cover was provided for the clams which remained in static seawater during low tides.

The clams were measured and weighed monthly. Daily monitoring included reading and recording of minimum-maximum temperatures and checking of tanks for dead clams.

Results

Growth

The length and weight increments of the clams over the 5-month study (August 1986 to January 1987) are shown in Table 1. A mean of 5.28 mm/month was obtained for 9.5-month-old clams and 2.57 mm/month for 18.5-month-old clams. Mean monthly weight increments of the younger clams were 2.86 g/month and 15.88 g/month for the older clams.

Two tailed tests on the monthly length and weight increment of both ages revealed that younger clams had significantly higher length increments ($P < 0.05$) and the older juveniles had significantly higher weight increments ($P < 0.05$).

Survival

The monthly percent survival of clams throughout the study is shown in Table 2. Mean percent survival ranged from 93.7 to 98.7 for the first 4 months. Heavy mortality occurred in January.

Discussion

Mean monthly length increments of *T. gigas* juveniles (ca 40 mm) in the field in Pioneer Bay ranged from 6.5 to 10.7 mm (Crawford et al. 1988). Values obtained for clams reared here in intertidal ponds were lower than the lowest mean value they obtained (clams in floating racks).

Although no protective cover was provided for the clams, no predation was observed. The biggest problems were the accumulation of silt in the tanks and the increase of water temperature during the long periods between high tides. Water temperature regularly reached 31°C, but this did not cause high mortality, during the first few months of the study. With the progress of summer, water within the tanks reached a maximum temperature of 35°C, which appears to be largely responsible for the mortalities during the later months. Loss of zooxanthellae, as

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TABLE 1. Mean growth of *T. gigas* juveniles in an intertidal pond in Pioneer Bay (n = 160).

Tray number	9.5-month-old		18.5-month-old	
	Length (mm/month)	Weight (g/month)	Length (mm/month)	Weight (g/month)
1	5.48	3.31	2.43	18.4
2	5.29	2.85	2.72	17.1
3	5.11	2.55	2.44	13.3
4	5.23	2.71	2.69	14.7
Mean	5.28	2.86	2.57	15.9

TABLE 2. Monthly percent survival of *T. gigas* juveniles in intertidal ponds (n = 160).

Tray number	9.5-month-old					18.5-month-old				
	Sept. '86	Oct.	Nov.	Dec.	Jan. '87	Sept. '86	Oct.	Nov.	Dec.	Jan. '87
1	-[a]	-	-	-	75	-	-	-	-	40
2	-	-	-	-	60	-	-	-	-	40
3	-	95	85	80	75	-	-	95	95	25
4	-	-	95	95	95	-	-	-	-	95
Mean	-	98.75	95	93.75	76.25	-	-	98.75	98.75	50

[a] - = 100% survival.

manifested by the bleaching of the mantle, was observed.

The low survival during the later months agrees with laboratory experiments of *T. gigas* juveniles wherein low survival at high temperatures was observed (S. Mingoa, unpublished data).

The intense heating of the static water within the tanks during the summer months could have been minimised if high tides occurred during the day. The incoming tide could have offered protection from the intense sunlight and replaced the static warm water with fresh cooler water. Also, the tide could bring in nutrient-rich seawater to replace the nutrient-depleted water in the ponds. The clams in the intertidal ocean nursery at Pioneer Bay had high shell increments despite exposure during very low tides and heating of surrounding water during low tides. However, with the continuous supply of fresh seawater, nutrients within the immediate surrounding water will not be depleted.

Conclusion

Results of the study indicate that although the ponding of clams is favourable to survival (in terms of predation-caused mortalities), growth is slow. This could have been caused by the combined effect of high water temperature within the ponds and the depletion of nutrients during periods of static pond water.

Acknowledgment

Janet S. Estacion would like to acknowledge the financial support of ACIAR (Australian Centre for International Agricultural Research) for supporting her travel to James Cook University, Townsville. The help of Warwick Nash, Stephane Westmore and the others in the continued monitoring of clams is also gratefully acknowledged.

Interspecific Growth Rates of Cultured Giant Clams on the Great Barrier Reef

C.M. Crawford*, R.D. Braley and W.J. Nash***

Abstract

Growth rates for up to 3 years of the cultured juveniles of the four largest species of giant clams are compared at two sites, Orpheus and Lizard islands, on the Great Barrier Reef. At both locations *T. gigas* consistently had the highest growth rate and *T. derasa* the lowest. *Tridacna squamosa* grew slightly faster than *T. derasa* at Orpheus Island. The growth rate of *H. hippopus* was variable but overall was between that of *T. gigas* and *T. derasa* at Lizard Island. A seasonal pattern of growth was obvious in all species at Orpheus Island, especially in *T. gigas*.

THERE has been considerable speculation but few measurements on the differences in growth rates between the species of giant clams. Growth rates are particularly important when selecting a species for mariculture. Heslinga et al. (1984) at the Micronesian Mariculture Demonstration Center in Palau chose *Tridacna derasa* as the species to concentrate their culture activities on because of its fast growth in the region, safety from predation at an early age because of its thick shell, and ease of handling the broodstock. On the Great Barrier Reef (GBR), however, *Tridacna gigas* has been considered the prime candidate for mariculture by both the ACIAR-funded research team and private enterprise, mainly from conjecture that it is the largest species of giant clam and therefore should have the highest growth rate. The ACIAR-supported group, working on Orpheus Island, have also attempted to culture the other larger species of giant clams to examine their potential for mariculture and as a comparison to *T. gigas*. In particular, their survival and growth rates under different environmental conditions have been investigated, although on a smaller scale than for *T. gigas*.

The results presented in this paper describe and compare the growth over the first few years of four species of giant clams, *T. gigas, T. derasa, T. squamosa* and *Hippopus hippopus*, which have been cultured at Orpheus Island, and also some growth data from Lizard Island, on the GBR (Braley 1986, unpublished data).

Culture Methods

Broodstock clams of three species were collected from the fringing reefs of the Palm Island group. *Tridacna derasa* is uncommon in the Palm Islands and broodstock was collected from Bramble Reef, a mid-shelf patch reef. They were spawned either naturally or after induction with serotonin. The clams were reared through the hatchery and nursery phases using the methods of Crawford et al. (1986). Several methods were tried during the ocean-nursery phase. As the principal aim of this research was to determine the most practical and economical techniques for cultivation, different methods were tested and refined as more information became available. Thus different spawning batches were reared using several methods and under different environmental conditions. Statistical comparisons of the growth rates, therefore, were not made. These methods are described in detail by Crawford et al. (1988) and in Barker et al. and Braley et al. (This Monograph).

The shell lengths of 50 clams of each group were measured wherever possible at intervals of every 1–2 months.

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Results and Discussion

Both batches of *T. gigas* juveniles showed marked seasonal variation in growth rate, with the slowest growth generally occurring during winter and early spring (Fig. 1a,b). Over the first 2 years the October 1985 spawning batch had a higher growth rate than the February 1985 spawned juveniles. This may be partly genetic, but also may be because the February 1985 juveniles were the first reared on Orpheus Island and were subjected to least favourable rearing conditions. As well, measurements were made of juveniles under different conditions, with most measurements on the February 1985 batch being from juveniles in subtidal ocean-nursery boxes. Subsequent research has shown that growth rates of *T. gigas* are lower in the subtidal benthic zone than in the intertidal zone (Crawford et al. 1988). The two most recent measurements of February 1985 juveniles are from intertidal boxes which probably accounts for the very high apparent growth rate of juveniles 30–36 months old (Table 1).

The *T. derasa* juveniles spawned in September 1985 grew markedly slower than the *T. gigas* juveniles, and after 2 years were approximately half the size. Seasonal changes in growth rate also were less obvious than for *T. gigas* (Fig. 2, Table 1).

Hippopus hippopus juveniles have been reared for only 12 months at Orpheus Island. The growth rate of this species was slightly higher than for *T. gigas* over the first 12 months, and was particularly high during the latter 6 months of spring and summer (Fig. 3). Measurements over a longer period of time, nevertheless, are required to determine whether this rate continues.

The juveniles from the two spawnings of *T. squamosa* also had different growth patterns (Fig. 4a and b). The March 1985 juveniles grew quickly during their first spring and summer, but were slower in their second and third years. The January 1986 *T. squamosa* juveniles had a consistent growth rate over the first 2 years. The growth during the

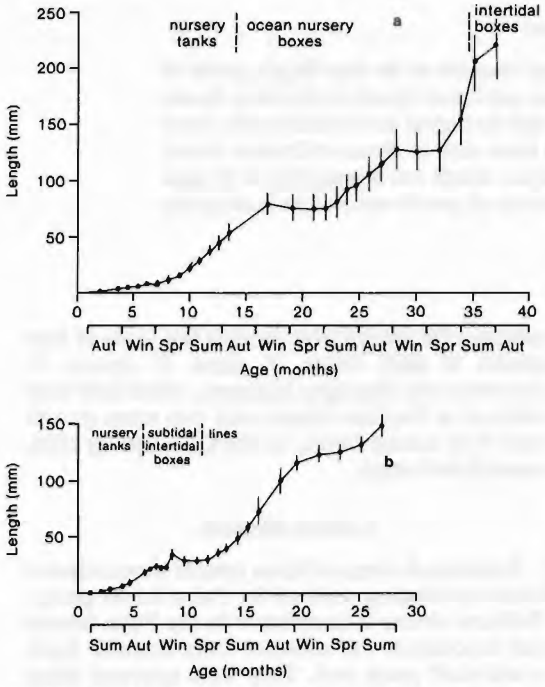

Fig. 1. Mean length ± SD over time of *T. gigas* juveniles (a) spawned 1 February 1985 and (b) spawned 21 October 1985. Rearing methods are indicated at the top of the figure.

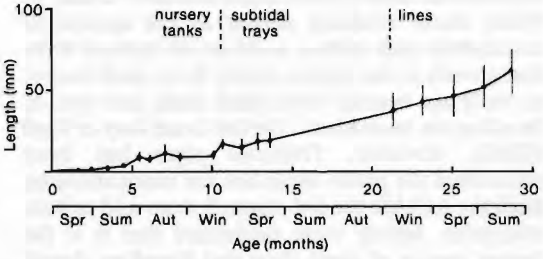

Fig. 2. Mean length ± SD over time of *T. derasa* juveniles spawned on 17 September 1985.

TABLE 1. Daily growth increments in shell length (mm) over six monthly periods (0–6 months, etc.) of four species of giant clams at Orpheus Island. Spawning dates for each species are shown in parentheses.

Age (months)	*T. gigas* (1-2-85)	*T. gigas* (21-10-85)	*T. derasa* (17-9-85)	*H. hippopus* (6-2-87)	*T. squamosa* (12-3-85)	*T. squamosa* (14-1-86)
6	0.04	0.09	0.05	0.04	0.02	0.03
12	0.18	0.08	0.05	0.22	0.23	0.07
18	0.20	0.37	0.08	-	0.07	0.08
24	0.09	0.16	0.08	-	0.03	0.07
30	0.18	-	-	-	0.09	-
36	0.49	-	-	-	0.09	-

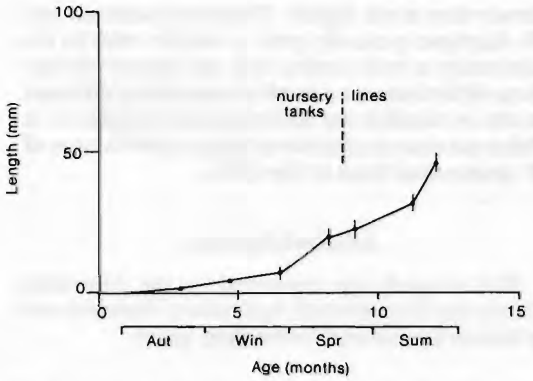

Fig. 3. Mean length ± SD over time of *H. hippopus* juveniles spawned on 6 February 1987.

first summer was probably retarded because they were overcrowded.

A comparison of the daily growth increments over six monthly periods, extracted from the growth curves of the four species (Table 1), indicates that *T. derasa* has the lowest growth rate. *Tridacna gigas* juveniles had variable growth patterns but overall had the highest growth rate over the 3-year period.

Growth data from Braley (1987) and subsequent unpublished data for three species of giant clams reared at Lizard Island show a similar pattern to the clams at Orpheus Island (Table 2). *Tridacna gigas* consistently had the highest growth rate and *T. derasa* the lowest. The daily growth increments of *H. hippopus* varied over the different time periods but were consistently between the other two species. After 3 years of growth of juveniles of the three

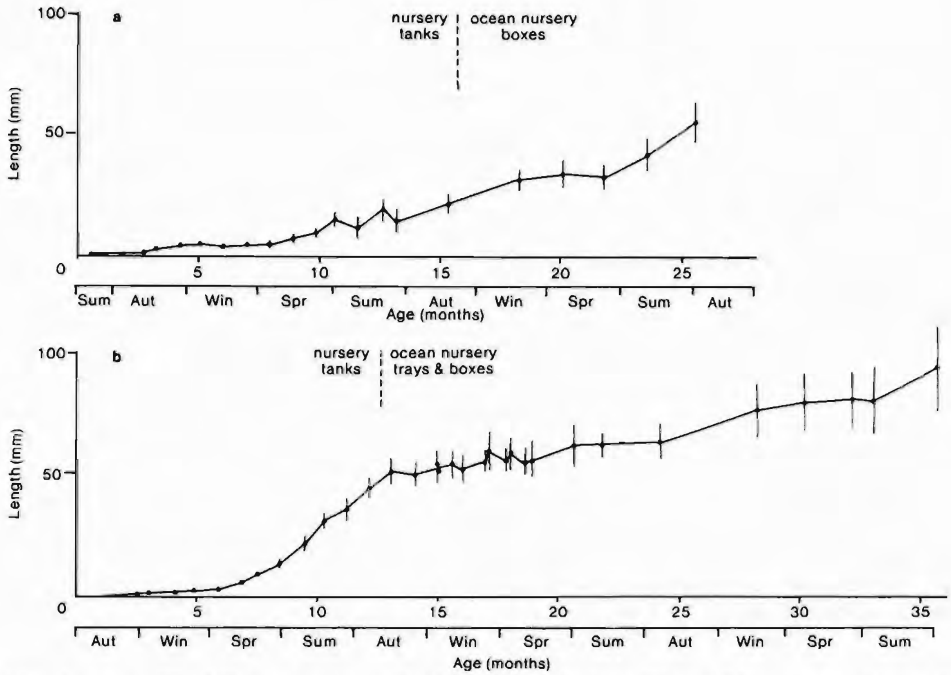

Fig. 4. Mean length ± SD of *T. squamosa* juveniles (a) spawned 12 March 1985 and (b) spawned 14 January 1986.

TABLE 2. Daily growth increments in shell length (mm) between measurement dates of three species of giant clams spawned at Lizard Island in late November/early December 1984. From Braley (1987 and unpublished data).

Age (months)	*T. gigas*	*T. derasa*	*H. hippopus*
7–10	0.17	0.03	0.12
10–12.5	0.22	0.05	0.12
12.5–16	0.13	0.02	0.09
16–25.5	0.11	-	0.12
25.5–35.5	0.12	0.07	0.08
Mean length at age 35.5 months (mm)	149.5	75.7	109.7

species that had spawned at the same time, late November to early December 1984, *T. gigas* juveniles were 1.4 times the length of the *H. hippopus* and almost twice the size of the *T. derasa* juveniles.

On the GBR *T. gigas* is thus the best species to culture if fast growth is required, while *T. derasa* appears to be the least suitable. These growth rates of *T. derasa* are much lower than those recorded in Palau (Heslinga et al. 1986). Of the data on growth rates presented by Munro and Heslinga (1983), *T. gigas* had similar growth rates in the laboratory to those recorded in this study, whilst those for *T. derasa* were much higher. *Tridacna squamosa* and *H. hippopus* generally grew at similar rates in the laboratory in both studies. It is not known whether these differences are a result of genetically different stocks or whether the environmental conditions in Palau are more conducive to higher growth rates of *T. derasa* than those of the GBR.

Acknowledgments

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Comparative Growth Rates for *Tridacna gigas* at Different Localities in Northeastern Australia

J.R. Barker*, J.S. Lucas* and W.J. Nash**

Abstract

An interlocality comparative growth rate study of *Tridacna gigas* was conducted for four localities on the Great Barrier Reef. Both subtidal and intertidal sites were used, as well as two different reef types. Both tidal heights were investigated at Orpheus Island, the intertidal at Magnetic Island and the subtidal at John Brewer Reef. Both islands are situated on the inner reef and John Brewer Reef is a middle patch reef. Two spawnings from February and October 1985 were used. Growth rates were faster at the intertidal, Orpheus Island site with a daily increment of 0.241 and 0.249 mm/day for the respective cohorts. The Magnetic Island and John Brewer Reef sites produced equal growth rates for the October cohort (0.199 mm/day). The intertidal site on Orpheus Island produced the slowest growth for the October cohort with a rate of 0.188 mm/day. A rate of 0.189 mm/day was obtained for the February cohort at this site. This cohort exhibited a similar growth rate of 0.175 mm/day at Magnetic Island. The slowest growth rate was for the February cohort at John Brewer Reef with an average daily increment of 0.147 mm/day. The different growth rates are accounted for in terms of available light and nutrients.

COMPARATIVE growth rates have been determined for *Tridacna gigas* grown under different exposure periods (Nash et al., This Monograph) and for different culture methods (Crawford et al. 1988). The only information available with respect to growth rates elsewhere on the Great Barrier Reef comes from Lizard Island (Braley 1986; Crawford et al., This Monograph). All of the above experiments have been conducted at single localities. No comparative growth rates for a single cohort of clams at different localities on the Great Barrier Reef are available.

Tridacna gigas were reared in the intertidal and subtidal zones at Orpheus Island, Magnetic Island and John Brewer Reef, near Townsville in the central GBR region. These allow a comparison to be made at different localities, over the same time period and for the same cohort. The intertidal zones at Orpheus Island and Magnetic Island are similar in that they consist of fringing reefs surrounding a mainland island. Magnetic Island generally has more turbid water and is slightly more exposed to wave activity than Orpheus Island. John Brewer Reef is a mid-shelf reef and as such does not have the protection afforded by an island. However, the expectation is that the water clarity should be higher and therefore offer reasonable growing conditions for the clams. This is a subtidal locality and the growth rates can be compared with the mainland subtidal site.

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Materials and Methods

The *T. gigas* juveniles used in this study were spawned and reared at Orpheus Island Research

Station following the techniques outlined in Crawford et al. (1986). They were from two successive spawning seasons in February and October 1985. Both groups were kept in the onshore tanks until large enough to be transferred out to the ocean nursery phase of culture (Crawford et al. 1988). The February-spawned cohort was placed in a protective cage in the intertidal region at Orpheus Island for 2 months prior to its transfer to the experimental sites. The October cohort was transferred directly from the onshore nursery phase. Fifty clams of each group were initially introduced to each site.

At Orpheus Island, the intertidal and subtidal sites were in Pioneer Bay. This enabled the comparison of subtidal versus intertidal growth rates to be made within the same locality. The intertidal site was at the northern end of the bay at approximately 0.6 m above chart datum. The subtidal site was towards the centre of the bay beyond the reef flat at approximately 5 m mean depth. The Magnetic Island site was in the intertidal zone at approximately 0.5 m above chart datum in White Lady Bay on the east coast of the island. At John Brewer Reef the site was subtidal on a flat area of coral protected on all sides by coral bommies at approximately 4 m mean depth. No intertidal site was chosen at John Brewer Reef due to potential damage to equipment and clams from the frequently high levels of wave action.

At all sites the clams were housed in protective boxes made from galvanised steel of 100 mm square mesh covered by plastic mesh of 25 mm square (Barker et al., This Monograph). Within the cages a substrate of either gravel or coral rubble was used depending on the availability of the material. This allowed for the removal of the clams during subsequent measuring without the trauma associated with severing the byssus.

Measurements were taken at intervals from December 1986 using shell length as the measure of comparative growth rate. All measurements were taken using vernier calipers to an accuracy of 0.5 mm due to irregularities in the shell margin.

Results

There were substantially faster growth rates of *T. gigas* at the intertidal site on Orpheus Island (Fig. 1,2), especially over the first 4-6 months of 1987. This is substantiated by the average daily growth rate under experimental conditions (Table 1). For both cohorts the average growth rate at the intertidal site on Orpheus Island is approximately 1.3 times faster than the subtidal site. Each cohort exhibited an approximately equal incremental increase per day at each of the two sites at Orpheus Island.

There was slower growth of the February cohort

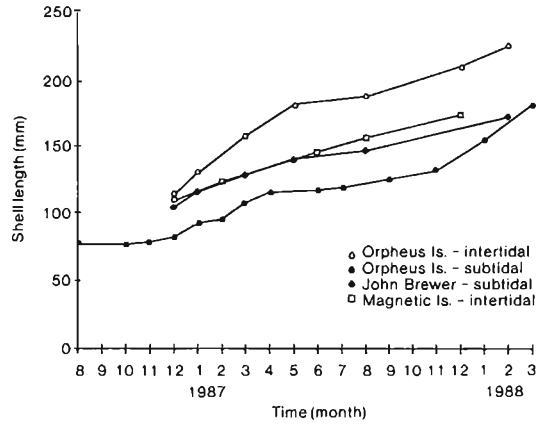

Fig. 1. *Tridacna gigas* growth rate; February 1985 spawning.

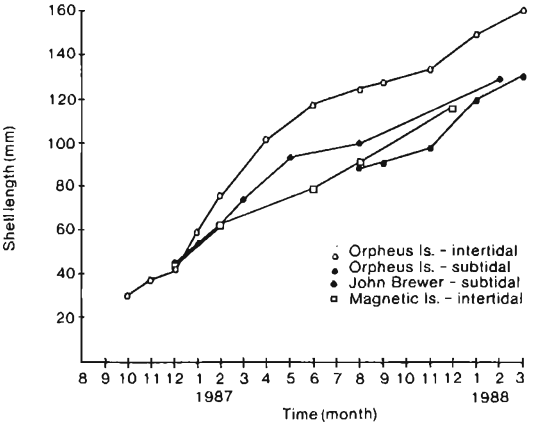

Fig. 2. *Tridacna gigas* growth rate; October 1985 spawning.

at Magnetic Island and John Brewer Reef than at the subtidal site on Orpheus Island. This appears to be due to the rapid increase over the 1987-88 summer period shown by those clams at Orpheus Island (Fig. 1). The situation was reversed for the October spawned cohort (Table 1), although there was little actual size difference at 2 years 5 months, as shown in Fig. 2.

There appeared to be a larger seasonality component to the growth rate at the Orpheus Island sites than at either of the others, although the John Brewer Reef clams showed a slight reduction in growth rate during the winter period.

Discussion

For the culture of *T. gigas* it would appear that the intertidal site at Orpheus Island was better than

TABLE 1. Locality and associated growth rate for *T. gigas*.

Locality – site	Mean change in size (mm)	Experiment duration (days)	Mean growth rate (mm/day)
February 1985 spawning:			
Orpehus Island			
subtidal	105.5	558	0.189
intertidal	107.8	448	0.241
Magnetic Island			
intertidal	62.8	358	0.175
John Brewer Reef			
subtidal	65.9	434	0.147
October 1985 spawning:			
Orpheus Island			
subtidal	42.2	224	0.188
intertidal	130.4	524	0.249
Magnetic Island			
intertidal	71.1	358	0.199
John Brewer Reef			
subtidal	84.5	424	0.199

the other three in this study. This agrees with Crawford et al. (1988) who suggest the intertidal as the more promising culture method compared to three other methods. When compared to the subtidal site at the same locality, the difference in growth rate is pronounced. This is probably largely due to the high light levels available to the symbiotic zooxanthellae in the intertidal zone. Although the subtidal site provides the zooxanthellae with the opportunity to photosynthesise for longer periods, i.e. without interruption by emersion, the rate is presumably much less due to water turbidity and depth. Therefore there would be a lesser supply of the necessary metabolic compounds produced by the zooxanthellae available to the clams. Summons et al. (1986) report on 'important interactions between light-dependent metabolic processes in symbiotic zooxanthellae and their hosts.' They found that photosynthesis was stimulated by the addition of ammonium to seawater. The runoff from islands is generally high in available nitrogen and phosphorus and as such may help to stimulate the growth of the clams from the increased photosynthetic rate of zooxanthellae. The assumption is that the relative levels of these nutrients are equal for different tidal heights at the same locality if it is light that is the determining factor for the observed difference in growth.

The reduced growth rate at the Magnetic Island site, as compared to the intertidal site at Orpheus Island, was not unexpected. The highly turbid nature of the water at Magnetic Island with the concomitant reduction in available light and photosynthetic rate is the most likely cause of this finding, although there is no comparative information as to the levels of nitrogen and phosphorus available to the symbiotic algae. There may also be a higher wave disturbance factor at Magnetic Island due to the lesser degree of shelter afforded to the site. Disturbance as noted in Lucas et al. (in prep.) has the potential to slow growth.

The faster growth rate of the October cohort at John Brewer Reef, as compared to the subtidal site at Orpheus Island, can probably be attributed to the clarity of the water column. Biofouling by algae is a slight problem at the Orpheus Island subtidal site; however, biweekly cleaning of the upper surface of the boxes negates this as a possible cause of the slower growth. At John Brewer Reef the herbivorous fish populations keep biofouling down to a minimum.

The essentially equivalent overall growth at the Magnetic Island and John Brewer Reef sites appears to contradict the Orpheus Island finding of intertidal/subtidal differences. There are two possible reasons for the equality in the growth at these sites. First, the difference in depth should favour growth at the Magnetic Island site. Second, the water clarity at John Brewer Reef would favour it. There is most likely a balance between the different factors involved in the growth of the clam which together combine to produce essentially equal growth rates at these two localities. It would appear that the increased depth and probable lower levels of free nitro/phosphorus compounds at John Brewer Reef is enough to offset the greater clarity of the water to significantly reduce the photosynthetic rate of the zooxanthellae.

From this study there are two major conclusions. The first is that, for ease of maintenance and potentially faster growth rates of the giant clams, intertidal localities are preferable. Second, the water

turbidity can be extremely high, as it frequently was at Magnetic Island, and yet *T. gigas* will still grow successfully. Further work needs to be completed on quantifying the physical parameters at separate localities to accurately determine the influences on growth rates.

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Growth of Laboratory-Reared Giant Clams Under Natural and Laboratory Conditions

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Abstract

Tridacna derasa, T. squamosa, T. maxima, Hippopus hippopus and *H. porcellanus* were reared from larvae to 1- to 3-year-old juveniles in outdoor, sunlit wooden raceways in flowing water. Growth was monitored and growth rates estimated. The results are presented together with results of small-scale experiments. Comparisons were made in growth of juveniles placed in three interconnected raceways and of three size-classes in the laboratory and in the field. The effect of increased nitrate concentration on growth and survival of juveniles was measured, as was the growth and survival between laboratory- and field-reared clams.

THE Silliman University Marine Laboratory (SUML) has been involved since 1984 in a collaborative research program supported by the Australian Centre for International Agricultural Research (ACIAR) on the culture of giant clams for food and restocking of tropical reefs. To date, six species of tridacnid clams have been successfully induced to spawn in the laboratory: *Tridacna derasa, T. squamosa, T. maxima, T. crocea, Hippopus hippopus* and *H. porcellanus*. Except for *T. crocea*, the larvae of the other five species have also been successfully reared to 1–3-year-old juveniles in outdoor sunlit wooden raceways provided with running seawater. As one of the objectives of the program, these juveniles have been used in several growth experiments under natural and laboratory conditions to determine maximum rates of growth in both conditions. According to Munro and Heslinga (1983), factual data on the maximum rates of growth achievable by juvenile tridacnid clams remains the critical determinant of whether maricultural operations will be feasible.

This paper presents growth of *T. derasa, T. squamosa, T. maxima, H. porcellanus* and *H. hippopus* from a fertilised egg to 1 year of age and results of small-scale experiments of these laboratory-reared juveniles under natural and laboratory conditions.

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Materials and Methods

The fertilised eggs of *T. derasa, T. squamosa, T. maxima, H. hippopus* and *H. porcellanus* were allowed to develop in larval-rearing cement tanks with shaded plastic roofing. Larvae of *T. derasa*, however, were reared in a cement tank with transparent plastic roofing. Samples of the larvae in every stage were measured for size with a micrometer eyepiece. Size measurements, in terms of shell length measured along the longest axis, were expressed in means ± standard deviation. When most of the juveniles had reached 3–4 months old, they were transferred to sunlit wooden raceways. Lengths of these juveniles in raceways were taken periodically using a plastic vernier caliper to measure growth.

Comparison of Growth

To determine whether the position of the laboratory raceways placed at different distances from the seawater inlet affects growth of juveniles, 6-month-old juveniles of *H. hippopus* were

monitored. These animals were placed for 4 months in three short raceways, 240 cm long × 120 cm wide × 50 cm deep, interconnected to each other end to end with two 60 cm long and 5 cm diameter polyvinyl chloride (PVC) pipes serving as inlet and outlet pipes. The clams were tagged then divided into groups of 30 individuals per raceway and placed near the inlet portion. Water temperature, salinity, and dissolved oxygen were determined periodically, as was volume flow and presence of microoganisms in each raceway. Each clam was measured monthly. Monthly mean shell lengths were tested with 1-way ANOVA to determine if there was variation due to differences in growth between raceways in each month. Thus four separate analyses were done for the first, second, third and fourth months with the three raceways as the factor. Total growth in length and growth rates (mm/month) after 4 months were also estimated for each raceway.

Growth Determination

This small-scale experiment was conducted to determine whether juveniles of similar ages but of different sizes have similar growth and growth rates both in the laboratory raceways and in the field. Three size-classes, small, medium and large, based on the prevailing sizes of the available clams, were formed using 9-month-old *H. hippopus*. Each clam was measured and a size range for each class consisting of 30 individuals was determined. Clams within the range of 16–19 mm belong to the small class; 26–29 mm to the medium class; and 39–42 mm to the large class. These were allowed to grow for 8 months in the laboratory raceways and also in the field at Balicasag Island. However, clams in the field suffered heavy mortalities after the first month, and another set of animals from the same batch, but larger sizes were used. This set had ranges of 20–25 mm, 35–40 mm and 50–55 mm for small, medium and large classes, respectively. These animals were allowed to grow in the field for 7 months and then were measured.

Effect of Increased Nitrate Concentration

This experiment aimed to show the feasibility of improving growth and even survival of clams through increased nitrate concentration which may supplement their nutrient requirements. One hundred and sixty individuals of 1-year-old *H. hippopus* with sizes ranging from 29 to 38 mm were selected as experimental animals. The shell length of each animal was measured using a small plastic vernier caliper. The clams were tagged using labelled waterproof paper that was glued on the shell with marine epoxy. These were then placed in four separate glass aquaria, 60 × 30 × 40 cm, with a stocking density of 40 clams/aquarium. Each aquarium contained 50 l of unfiltered seawater that was fully circulated twice a week. Three of the aquaria served as replicates for increased nitrate concentration and one as control. The nitrate concentration of the seawater was determined prior to the addition of sodium nitrate, but the concentration was too small to be detected by the chemical analysis. One gram of sodium nitrate equivalent to 14.6 ppm of nitrates was added after 1 hour of flow-through. Water temperature and salinity were monitored daily and dissolved oxygen was measured once a week. Growth of clams was monitored once every 6 weeks by measuring the clam's shell length.

Laboratory vs Field Growth and Survival

The growth and survival of clams of different ages in the natural reef as compared with that of the laboratory were investigated using 90, 5-month-old *H. hippopus* and 90, 13-month-old *T. maxima*. These clams were placed at Apo Island reef in cages made of plastic trays with iron bar framing, measuring 35 cm long × 30 cm wide × 10 cm deep, and covered with nylon screen in 5 m of water. Those at the laboratory raceways with the same number of clams were placed in plastic trays (of the same dimension as those cages in the field) in 0.5 m of water. But due to the high mortality of clams caused by predation and wave action encountered in the reef in the first trial, another group consisting of 100, 10-month-old *H. hippopus* was placed in the same reef and another consisting of 100, 11-month-old at Bantayan Reef. The latter group was placed in a bigger cage made of iron bars with nylon netting (1 m long × 0.5 m wide × 0.75 m deep) in 3 m of water. Juveniles of equal number and similar ages with those in the field were also placed in the laboratory raceways. Growth of these clams was then compared with those in the field.

Results

Hippopus hippopus, H. porcellanus, T. derasa, T. maxima and *T. squamosa* achieved mean lengths of 66.6, 61.4, 43.4, 38.3 and 34.9 mm, respectively, at 1 year old. A monthly growth rate of 5.5, 5.1, 3.6, 3.2 and 2.9 mm was estimated respectively. Three-year-old *T. maxima* reached a mean length of 62.5 mm with a monthly growth rate of 1.74 mm. Thirty-one-month-old *H. hippopus* reached a mean length of 105 mm with a monthly growth rate of 3.4 mm.

Growth in Interconnected Raceways

Results of 1-way ANOVA on growth and growth rates of *H. hippopus* revealed no significant differences between raceways ($P > 0.05$) in all of the 4 months tested and after 4 months. Table 1

TABLE 1. Mean growth of *H. hippopus* juveniles after 4 months in three laboratory raceways connected in series (1 to 3).

Raceway	*n*	Initial mean (mm ± SD)	Final mean (mm ± SD)	Growth (mm ± SD)	Growth rate (mm/month)
1	30	16.6 ± 4.4	50.3 ± 8.6	33.7 ± 5.7	4.3
2	30	15.5 ± 3.5	50.8 ± 3.5	35.3 ± 3.2	4.9
3	30	17.2 ± 4.9	52.3 ± 3.2	35.7 ± 3.2	4.6

TABLE 2. Mean growth of three size-classes of *H. hippopus* juveniles in the laboratory and field.

Size classes	*n*	Growth (mm ± SD)	Growth rate (mm/month)
A. Laboratory			
Small (16–19 mm)	30	20.7 ± 5.8	2.6
Medium (26–29 mm)	30	30.2 ± 5.5	3.7
Large (39–42 mm)	30	28.9 ± 6.1	3.6
B. Field			
Small (20–25 mm)	30	28.7 ± 6.8	4.1
Medium (35–40 mm)	30	28.9 ± 7.1	4.1
Large (50–55 mm)	30	32.1 ± 7.5	4.6

TABLE 3. Mean shell length (mm ± SD) of *H. hippopus* (n = 40/aquarium). Replicates A–C were treated with nitrate. The control was not. T0 — start of experiment (12-month-old clams). T1 — after 1.5 months. T2 — after 3 months.

Aquarium	T0	T1	T2
Replicate A	33.4 ± 1.8	38.4 ± 3.8	42.5 ± 4.8
Replicate B	36.0 ± 2.4	42.6 ± 4.8	46.5 ± 5.4
Replicate C	32.6 ± 1.8	40.5 ± 4.2	45.5 ± 5.1
Control	29.4 ± 1.1	31.2 ± 2.2	32.9 ± 2.9

shows growth achievement by *H. hippopus* and its growth rates after 4 months. Individual clams were observed to have variable growth and growth rates. Water temperature fluctuated between 25 and 30°C while salinity was fairly constant, averaging 32.4 ± 0.4 ppt. Dissolved oxygen (DO) content of the seawater ranged from 6.4 to 7.4 ppm. Volume flow of seawater to each raceway was equal at 56–60 l/min. The three raceways were found to contain the same kind of microorganisms of which some could serve as food for the clams, namely, *Chaetoceros* sp., pennate diatoms, desmids and unicellular algae resembling *Tetraselmis* and *Isochrysis galbana*.

Growth by Size-Class

Growth and growth rates of juveniles belonging to the medium class in the laboratory is significantly higher ($P < 0.05$) than those belonging to the small class but almost the same as those of large sizes. In the field, growth and growth rates of juveniles belonging to small, medium and large classes have no significant differences ($P > 0.05$) (Table 2).

Growth in Increased Nitrate Conditions

Pooled estimate of variance test showed probability values < 0.05 indicating that growth of clams with increased nitrate concentration is significantly higher than those grown in unfiltered seawater only. The mean growth of 1-year-old clams after 1.5 months and after 3 months, measured as increase in shell length, is shown in Table 3. The clams attained a monthly growth of 3.03, 3.49 and 4.29 mm for samples A, B and C, respectively, and 1.16 mm for the control. Variation in survival after 3 months was noted: 97.5% in sample A, 100% in sample C and only 70% in the control.

Water temperature in all aquaria was maintained at 28–30°C. Salinity ranged from 32 to 34 ppt and DO at 7.5–11 ppt.

Field vs Laboratory Growth and Survival

The results of experimentation on growth and survival of juveniles of different ages in the natural reef and laboratory are shown in Table 4.

TABLE 4. Growth of juveniles in the laboratory and field.

Species	Age (months)	Initial length (mm ± SD)	Final length (mm ± SD)	Growth (mm)	Growth rate (mm/month)	No. of months of study	% Survival
H. hippopus	5	Lab					
		18.95 ± 2.3 (15–30)	36.7 ± 5.1 (28.4–47)	17.75	5.9	3	98.9
		Field[a]					
		21.3 ± 3.3 (15–29)	38.3 ± 7.7 (20.4–50.8)	17	5.6	3	73.3[c]
H. hippopus	10	Lab					
		51.3 ± 6.5 (19–71)	68.5 ± 4.5 (61–73.5)	17.2	4.3	4	100
		Field[a]					
		52.1 ± 4 (33–60.6)	82.4 ± 5.4 (66–91)	30.3	7.57	4	66 [c]
H. hippopus	11	Lab					
		54.6 ± 5 (45–66)	84.6 ± 8.5 (69–107)	30	2.5	12	100
		Field[b]					
		55.5 ± 3.8 (50–66)	85.4 ± 9 (70–100)	29.8	2.56	12	65
T. maxima	13	Lab					
		32.9 ± 6.2 (20–40)	40.69 ± 7.3 (23–58.7)	7.79	2.59	3	94.4
		Field[a]					
		31.7 ± 5.6 (20–58)	41.4 ± 6.6 (33–60.6)	9.7	3.2	3	76.6[c]

[a] Apo Island Reef.
[b] Bantayan Reef.
[c] Experiment discontinued the following month due to 0 survival.

Laboratory-reared 5-month-old *H. hippopus* grown in cages in the field for 3 months had almost the same growth rates as those in the raceways. Mean length increased by 17.75 mm for clams in the raceway while field clams increased by 17 mm. However, 10-month-old *H. hippopus* grown in cages grew faster than those in the raceways and those 5 months old grown in the field. Similarly, field-grown *T. maxima* grew faster than those in the laboratory. But survival of clams at Apo Island reef for all setups was low, and experimentation had to be cut short. Total mortality was recorded in the succeeding months of the studies. Eleven-month-old *H. hippopus* grew from a mean length of 54.6 mm to 85.4 mm during the next 12 months in the field; the monthly growth rate was 2.56 mm. Those at the laboratory grew to a mean length of 84.6 mm from 54.6 mm; the monthly growth rate was 2.5 mm. Survival of these clams was higher in the laboratory than in the field for the same time period.

Discussion

The growth curves of the five species show similar characteristics. Growth was slow in the first 2–3 months and then accelerated during or after the third month, which corresponds to the time at which the juveniles were transferred to sunlit raceways. However, the growth curve of *T. derasa*, which had been in a sunlit larval tank, is comparable with other species.

At the University of the Philippines Marine Science Institute (UPMSI), a sharp increase in growth for laboratory-reared *H. hippopus* and *T. maxima* occurred on the 62nd day (UPMSI 36th Month Report). Jameson's (1976) *T. maxima* started to increase growth on the 40th day and *H. hippopus* on the 27th day. According to Jameson (1976), this corresponds to the time at which the majority of juveniles had acquired zooxanthellae. Animals probably show low growth rates from day 2 to the acquisition of zooxanthellae because energy is being channeled to various developmental stages leaving less available for growth in shell length. Increased growth rates after the acquisition of zooxanthellae are probably brought about in large part by the zooxanthellae themselves (Jameson 1976). Zooxanthellae have been found to supply *T. maxima* with energy from photosynthates (Goreau et al. 1973).

The fast growth attained by the *Hippopus* species in contrast to *T. derasa* in the laboratory might have been attributed to factors such as water

temperature, depth of rearing tanks, stocking density and egg size. *Tridacna derasa*, a fast-growing and the second largest species, was expected to reach a mean length of 50 mm after 1 year, which is normally attained by this species in Palau (Heslinga and Fitt 1987). On the other hand, *H. hippopus*, the third largest species, attained the highest growth among the five species reared from egg, followed by *H. porcellanus*. One-year-old clams in this study are smaller than those 1-year-olds in Palau (Heslinga et al. 1984). The slow growth of *T. derasa* may be attributed to the size of its egg (104.3 μm), which is small, in contrast to the size of *Hippopus* eggs (143.5 μm). Fitt et al. (1984) hypothesised that those eggs with larger nutrient stores, which may be reflected in egg size, would grow faster. The fast growth of *H. porcellanus* could have been affected by the stocking density upon rearing although not much is known of its growth. This species underwent mass mortality after the third month, and only 22 individuals survived until the first year.

First-year growth of *T. squamosa* may have also been affected by high stocking density in the tank (reared together with 4000+ of *H. hippopus*) as opposed to *T. maxima* (1000+) which is a smaller species. However, our 1-year-old *T. squamosa* are larger (34.8 mm) than Palau's (32.2 mm) (Heslinga et al. 1984). Juveniles growing in physical contact with each other are stunted and have shell deformities (Heslinga et al. 1984).

Water temperature of 27–34°C (Alcala et al. 1986) and depth of rearing tanks (0.5 m) may have promoted the growth of *H. hippopus* juveniles in the laboratory. This species lives in warm and shallow water (0.5 m deep). But it should be mentioned that *T. derasa* in Palau is cultured in warm water (27–30°C) and raceways with shallow flowing water (0.5 m deep) (Heslinga et al. 1984). Thus, *H. hippopus*, which ranks third in size among giant clams, is capable of fast growth in the first year, but slows thereafter. For all species, except *T. maxima*, a size of about 50 mm might normally be attained in the first year under average conditions (Munro and Heslinga 1983). Our results showed that *H. hippopus* is capable of attaining growth to 66 mm. For *T. maxima*, our results agree with the statement of Munro and Heslinga (1983) who said that a year or two might be required to attain a length of 50 mm. Our results on low growth rates of juveniles of more than 1 year old support an earlier study with *T. maxima* in Australia which demonstrated that growth rates decreased with increasing age (McMichael 1975).

Juveniles 15 mm long may be reared for optimum growth in the laboratory raceways placed end to end, with the water intake at one end and the outlet at the other. This design provided similar conditions and/or sufficient growth requirements for the clams in each raceway so that growth of clams in the interconnected raceways did not differ significantly. Results of monthly monitoring of physicochemical parameters of seawater in the three raceways indicated that water flowing from the first to the third did not differ. This could be attributed to the fast flow of water in the raceways. Water temperature fluctuated between 25 and 30°C. Dissolved oxygen of seawater in the raceways was comparable to the DO of the surrounding sea, which ranged from 6.4 to 7.2 ppm. A low DO (6.4 ppm) was recorded only in the morning from water which was held overnight prior to flowing. Salinity was also within range (31–33 ppt). Microorganisms present which were considered good food for clams included *Chaetoceros*, *Tetraselmis*, *Chlorella* and *Isochrysis galbana* (dePauw 1981; Fitt et al. 1984).

The variable growth rates of individual clams under identical circumstances have been observed by several authors (Beckvar 1981; Munro and Heslinga 1983). Enormous differences in individual growth rates occur even between clams which appear to be of the same cohort (Gwyther and Munro 1981). Similar observations have been encountered in our studies. Juveniles in the laboratory of the same age grew at different rates, and medium-sized juveniles increased most in linear size. Juveniles in the field, regardless of size, grew at similar linear rates. However, considering growth in mass (approximately equal to length^3), the larger size clams were increasing much more in mass for the same length increment. The largest, medium and smallest groups of clams within the cohort maintained their relative positions. Trench et al. (1981) have suggested that species-specific strains of zooxanthellae might, at least in part, be responsible for differences in growth rates.

The results on increasing the nitrate concentration of the seawater show an improved growth and possibly survival of clams. Since the tropical seas have the lowest values of total inorganic nitrogen, an additional amount of nitrate in the water would supplement the nitrogenous nutrient requirement of the clams. This agrees with the results of Wilkerson and Trench (1986) which showed faster growth of *T. gigas* clams by increasing concentration of dissolved inorganic nitrogen from ambient to 32 μM. A similar effect of elevated nutrients from fish defaecation is found to stimulate growth of corals (Meyer et al. 1983; Meyer and Schultz 1985a, b). Muscatine et al. (1984), used ammonium ions (NH_4) to measure the assimilation of inorganic nitrogen by zooxanthellae and to calculate the nitrogen-specific growth rates. Using the balanced-growth method, their results suggested that an average of 96% of the inorganic nitrogen assimilated by zooxanthellae was translocated to the

host.

The growth and growth rates of 11-month-old *H. hippopus* at Bantayan Reef had almost the same value as those in the laboratory after 1 year. Similar observations were also made by the University of the Philippines Marine Science Institute (UPMSI 1987). Growth of clams in the field, which was expected to be higher than laboratory-reared clams, was probably affected by rough seas and strong currents, which occurred during the sampling period from January to April and in August. Beckvar (1981) reported that strong currents may induce thick shell growth. Thus, a faster increase in shell length might be expected from clams placed in protected coves with slower currents. Preliminary results on growth studies in land- and ocean-based systems suggest that our land-based nursery can offer more or less the same growth potential as does the field of 5- and 11-month-old juveniles of *H. hippopus*, as well as better survival rates for juveniles. Apo Reef can provide good growth to juveniles, but not survival, while clams in Bantayan Reef had good survival but their growth was comparable to that in the laboratory. Holding clams for a longer time in the laboratory would be costly in terms of laboratory maintenance. Our results contradict those of UPMSI. They state that their ocean nursery offers fast growth and better survival for their juveniles (UPMSI 1987). In this case then a better site for our ocean nursery should be selected.

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Growth Rates of *Hippopus hippopus* from Orpheus Island, Great Barrier Reef

C.C. Shelley*

Abstract

The growth of *Hippopus hippopus* from tagged individuals at Orpheus Island, Great Barrier Reef, is described using the von Bertalanffy growth equation. Differences were found in asymptotic size and seasonal growth rate between sites. Clams transplanted from the littoral to sublittoral showed both increased values of L_∞ and K compared to their littoral growth. Minimum growth occurred in the 3 months preceding the annual spawning season at both sites.

GROWTH in bivalves has been shown to be determinate in most studies, so that growth in bivalves has been regularly described using the von Bertalanffy equation (Seed 1980). The importance of site-specific differences in growth has been described for several bivalves (Hickey 1987; MacDonald et al. 1987; Mallett et al. 1987).

This study examined differences in the growth of *Hippopus hippopus* between sites at Orpheus Island, with season, and between littoral and sublittoral habitats. Growth analysis was conducted assuming that the growth of giant clams approximates growth curves described by Brody (1945) and von Bertalanffy (1938).

Sites

Growth studies were carried out with *Hippopus hippopus* on the fringing reefs of Orpheus Island. The island is part of the Palm Island group situated within the Great Barrier Reef Marine Park. The island is a continental, high island, in the inner-shelf region of the Great Barrier Reef, although it is 12 km offshore (Parnell 1987).

There is a pronounced wet and dry season in this region. At Lucinda, on the mainland adjacent to the Palm Islands, 73% of the rainfall occurs between December and March (Barnes 1984). The surface seawater temperature ranges from 31.2°C in January to 21.8°C in July in Cleveland Bay, some 60 km south of the Palm Islands (Archibald and Kenny 1974). Winds are predominantly southeast, with a northeasterly component during the summer months (Barnes 1984; Johnson and Risk 1987).

During the wet season freshwater runoff from the mainland can lower the salinity considerably, the edge of low-salinity, freshwater plumes extending seaward of the Palm Islands. The salinity of seawater at the latitude of the Palm Islands can vary from under 32 ppt to over 35 ppt (Pickard 1977). The tidal range and tides at the Palm Islands are similar to those at Lucinda where the range is from MHWS 2.9 m to MLWS 0.46 m above chart datum (Parnell 1987).

Clams were tagged at two main sites: Pioneer Bay (n = 56) and Iris Point (n = 50 reef flat and n = 31 sublittoral site) on Orpheus Island.

The fringing reef at Iris Point is a reasonably exposed site, being open to wind and seas from the northeast to the southeast. The reef has several prominent 'steps' of algal terraces coming up from just below extreme low water springs to a shingle rampart, inshore of which is a shallow inner moat (maximum depth 0.5 m, mean depth 0.3 m relative to algal ridge height) in which *H. hippopus* is found.

Pioneer Bay is sheltered from the predominantly easterly winds, being only exposed to westerly winds, which are infrequent, and because the short reach over the sea for winds from the west usually

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results in little wave action. The reef flat is some 400 m wide.

Methods

Numbered aluminium tags were attached to *Hippopus hippopus* at each site. A small area of each shell was cleaned of algal growth using a wire brush, then a tag was pushed firmly onto the surface using adhesives designed specifically for use in water (e.g. Epijoint). The spatial position of clams was detailed on simple maps, which, whilst not drawn to scale or in great accuracy, were sufficient to relocate clams on a regular basis for remeasurement. Large floating buoys, stakes hammered into the reef and landmarks were used to relocate positions within sites. Shell length was measured to the nearest 1 mm using stainless steel vernier calipers. The calipers were fitted with extended plastic 'jaws' to lessen the chance of damaging shell ends and to provide a large surface area to hold against the shell end, so as to improve the accuracy of measurement.

Each clam was remeasured three times each visit and the mean of the three readings recorded. Clams were remeasured every 3 months where possible, from November 1984 to November 1986. The size-frequency of the clam populations at each site was recorded, as were observations relating to tagged clams and their habitat. At the Iris Point site, 31 *H. hippopus* were transplanted from the littoral to the sublittoral reef edge at a depth of 3.5 m below chart datum on a sandy bottom. This was to examine on a gross scale the effect of littoral factors such as regular strong wave action, and partial exposure on growth, by comparison with a sublittoral sample.

Analysis Techniques

The most commonly used growth function in fisheries science, von Bertalanffy (1938) has been rewritten in a number of ways for use in the analysis of mark-remeasure data. Three such methods which can utilise variable time intervals between measurements are those of Gulland and Holt (1959), Fabens (1965) and Munro (1982). These methods have recently been adapted for microcomputers. The basic analytical approach used to determine the parameters of the von Bertalanffy growth function for clams closely follows that of Munro (1982), Munro and Guyther (1981) and Pearson and Munro 1988 (in press). One difference between the methods described in Appendix 1 and methods employed in this study is that checking for suspect measurements was not carried out as detailed in Appendix 1 (e). For *H. hippopus* with a much smaller shell than *Tridacna gigas* or *T. derasa*, there is little error in caliper measurement, especially as each measurement was repeated three times. Also as seasonal differences in growth could give successive values of K which could be considered 'aberrant' in (e), the process was not carried out.

The specific growth rate (SGR) of the clams over different seasons was calculated to examine seasonal differences in growth. The equation of the SGR is usually:

$$SGR = \frac{(lnL_2 - lnL_1)}{t_2 - t_1}.$$

where L_1 and L_2 are lengths at times t_1 and t_2 respectively.

However, in an attempt to take into account size/age-related differences in growth, the SGR was divided by the average length of the clam over the measurement period so that a size-specific growth rate (SSGR) was calculated as follows:

$$SSGR = \frac{(SGR \times 1000)}{(L_1 + L_2)/2}.$$

Results

Habitat and Field Observations

At low water the depth of seawater in the Iris Point moat is maintained at a level of 1.2–1.3 m above chart datum. This results in all but a few *H. hippopus* on raised substrate being constantly immersed in the inner moat, except during ELWS tides when drainage from the moat results in partial emersion of many clams. Two areas on this reef had aggregations of *H. hippopus*. There was a distinct difference in size of individuals between the two locations within the site, thought to be a result of localised settlement within the lagoon in different years. Clams at the western site had a much larger average length (mean 260 mm — 11/85) than clams at the eastern site (166.9 mm — 11/85). The substrate on which *H. hippopus* is found in the inner moat consists of biogenic fragments and terrigenous gravels (Barnes 1984). A sublittoral site to which some *H. hippopus* were translocated was situated at the base of the reef slope, on sand. In Pioneer Bay *H. hippopus* is found in an area immediately inshore of the reef crest area (Fig. 1), which at LWS tides can be seen to be a slight depression in the reef flat, and is in a zone dominated by the coral *Montipora ramosa*. *Hippopus hippopus* is found on sand or coral rubble.

Individual *H. hippopus* were found still byssally attached at a shell length of 139 mm.

The *H. hippopus* sites at Iris Point Reef and Pioneer Bay were quite homogeneous, therefore no attempt was made to determine if there were intrasite-specific differences in growth resulting from differing microenvironmental variables. Only intersite differences were examined.

New shell growth could sometimes be detected at the growing shell edge of clams, as the shell was clean because algal colonisation had not kept pace with the new shell growth.

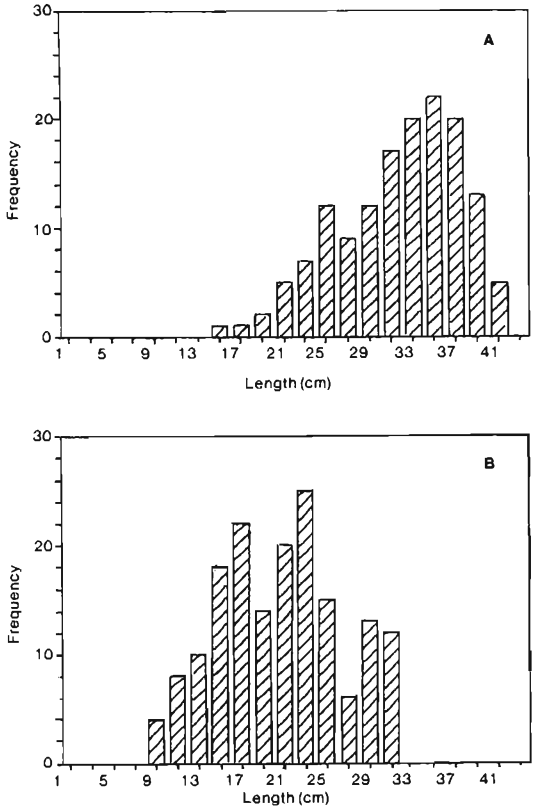

Fig. 1. Size-frequency distribution of *H. hippopus* at (A) Pioneer Bay and (B) Iris Point Reef.

The Iris Point site was affected by high winds and strong wave action resulting from Cyclone Winifred (1 February 1986). At the sublittoral site some *H. hippopus* were rolled several metres by the large waves associated with the cyclone.

A feature of *H. hippopus* at Iris Point Reef (11 August 1986) was that some had growing shell edges which noticeably overlapped, whereas usually they come together to a common point. This may be a result of tissue growth being outstripped by shell growth. The depth range for *H. hippopus* at Iris Point was 1–1.85 m above chart datum and at Pioneer Bay they were found at approximately 0.5 m above chart datum.

Growth Analysis

The size-frequency distribution of *H. hippopus* at Pioneer Bay (Fig. 1A) is almost unimodal, whereas at Iris Point Reef (Fig. 1B) three modes can be seen, although the overall impression is of a normal distribution. The modal size-frequency at Iris Point Reef was 12 cm less than at Pioneer Bay. One probable cause of this difference was that clams at Iris Point Reef were harvested occasionally by Palm Islanders, whereas those in Pioneer Bay, directly in front of the research station, were not. The Palm Islanders presumably selected the larger clams. Another difference between sites is that in Pioneer Bay no *H. hippopus* < 15 cm in shell length were found during the duration of the growth trial, whereas many more small individuals were found at Iris Point Reef (Fig. 1A,B).

Wetherall estimates of L_∞ and Z/K using all animals in the size-frequency sample are:

	L_∞	Z/K
Iris Point	305.4	0.86
Pioneer Bay	379.3	0.38

Plots of the mean annual length increment of successive length classes against mean length (Fig. 2A,B) showed that at neither of the two littoral sites were individuals still in their preinflexion growth phase, with increasing growth rate. The decreasing growth rate of the postinflexion growth curve of *H. hippopus* recorded in the mark-remeasure trials can therefore be described using the von Bertalanffy (1938) equation. These graphs indicate that there was little difference in growth rate for any given lengths of clams between the two littoral sites, though growth rates were slightly higher for clams at Pioneer Bay over the size range 180–240 mm.

Clams transplanted to the sublittoral off the edge of Iris Point Reef had improved growth rates compared to clams from the reef's intertidal zone (Fig. 2A). A few small clams were included in the sublittoral sample and this resulted in finding a point of inflexion in the plot of mean increment length against mean length of length class (Fig. 2A), which marks the change from an increasing to a decreasing growth rate with increasing length. The point of inflexion was in the length class 140–165 mm, the mean increment being 7.71 mm/year. The slope of the graph K^1, of $\log_e(Lr/Lm)$ against $r-m$ was 1.0834×10^{-3}.

To estimate the parameters of the von Bertalanffy equation, data triplets below the point of inflexion for the sublittoral clams were removed from the data set. The Fabens method was then applied to the modified data set to produce estimates of L_∞ and K.

Although the values of L_∞ for Iris Point are less than those for Pioneer Bay, the values of K are higher (Table 1). The sublittoral clams had a value of L_∞ intermediate between those of the two main sites, and the highest value of K.

Seasonal growth of *H. hippopus* examined by plotting SSGR against time showed that growth is minimal at both Pioneer Bay (Fig. 3A) and Iris Point Reef (Fig. 3B) in the last quarter of each year, the quarter prior to the start of the annual spawning season (Shelley and Southgate, This Monograph). The SSGR of Pioneer Bay was very high in

TABLE 1. Fabens estimates of parameters of the von Bertalanffy equation for *H. hippopus* from mark-remeasure trials.

Site	Data set	L_∞	K	n
Iris Point Reef	All triplets	347.40	0.2047	248
Iris Point Reef, sublittoral	Triplets less than inflexion removed	369.12	0.215	108
Pioneer Bay	All triplets	414.69	0.1549	388

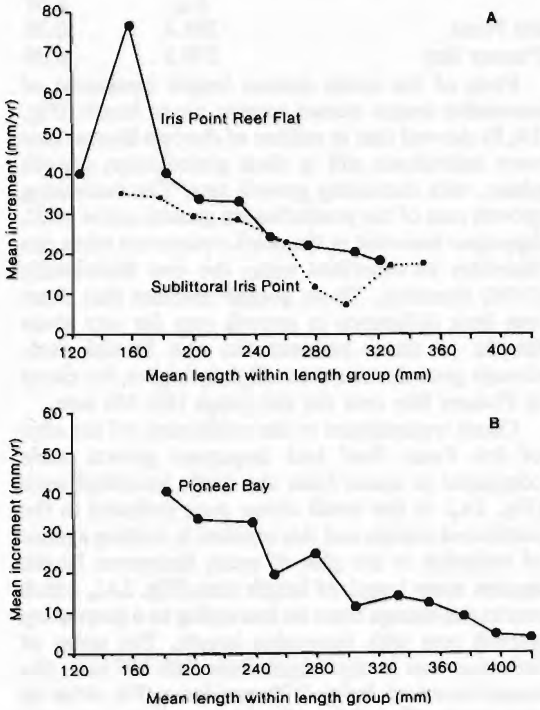

Fig. 2. Plots of the mean annual increment of successive length-classes against mean length within the length-class for *H. hippopus* at (A) Iris Point Reef and (B) Pioneer Bay.

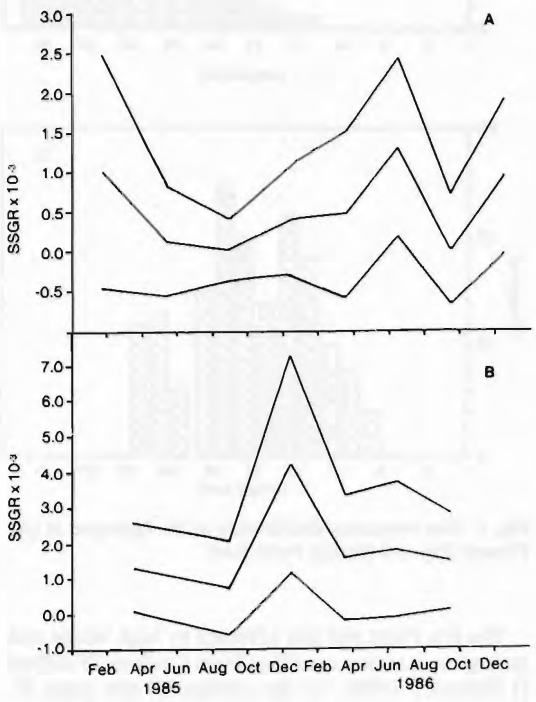

Fig. 3. Seasonal growth of *H. hippopus* at Pioneer Bay (A) and Iris Point Reef (B). Central line links mean values of the size specific growth rate (SSGR), whilst the upper and lower lines link values ± 1 SD of the mean.

midwinter 1985 and late winter of 1986. However, at Iris Point Reef SSGR peaked during the second summer quarter following the spawning season, so that the period of maximum growth differed between the two sites. The maximum value of the SSGR at Iris Point Reef was approximately twice that of the peak value at Pioneer Bay.

Discussion

Hippopus hippopus at Pioneer Bay showed a unimodal size-frequency distribution, skewed to the right. This is probably the result of rapid juvenile growth, followed by the overlapping of year-classes because of the variability of growth amongst individuals of any one year-class as described by Pearson and Munro (in press). The uneven size-frequency distribution at Iris Point Reef (Fig. 1) may reflect regular recruitment or the impact of harvesting on the resident clam population.

In Papua New Guinea, *H. hippopus* had a similar value of L_∞ (360 mm), but a lower K value (0.12) than clams at Orpheus Island (Table 1) (Munro and Gwyther 1981).

The Fabens (1965) technique has previously been shown to give the most accurate estimates of the

TABLE 2. Estimates of Z (instantaneous rate of mortality) for *Hippopus hippopus* at Orpheus Island.

	Wetherall estimates of Z/K	Fabens estimates of K	Z
Iris Point Reef	1.78	0.204	0.36
Pioneer Bay	1.75	0.154	0.27

von Bertalanffy equation (Sundberg 1984). The values of Z/K from the Wetherall method were used in conjunction with the Fabens estimate of K in the calculation of Z (the instantaneous rate of mortality) (Table 2).

The high value of Z for *H. hippopus* at Iris Point Reef reflects the fact that the population there was regularly harvested, so that the fishing mortality (F) had a direct impact on the total mortality Z, where $Z = F+M$, M being the natural mortality. Pearson and Munro (in press) showed that mortality rate varies with size for *T. gigas*. Therefore at best the mortality estimates presented here are estimates of the average mortality for all clams in the samples.

As the Wetherall (1986) technique gives a lower L_∞ compared to the Fabens (1965) technique for *H. hippopus* at both littoral sites, it could be argued that combining values from these two techniques to estimate Z (Table 2) is inherently inaccurate. However, for comparative purposes it is a useful exercise. The lack of any very small *H. hippopus* at both sites, together with the absence of any clams under 160 mm at Pioneer Bay, plus the patchy distribution of small clams at Iris Point Reef, indicate that significant natural recruitment is unlikely to be annual in the wild and that when it occurs it may occur on a very localised scale.

It appears possible that L_∞ is habitat-related as clams transplanted sublittorally had a different value to littoral clams and there was a difference between values in the two littoral sites.

Acknowledgments

I wish to thank the many field assistants who have helped at Orpheus Island, especially Ramy Kline and Emre Turak. Thanks also to the Orpheus Island Research Station management over the past 4 years. I was supported by a Commonwealth Scholarship and Fellowship Plan award for the duration of this study. Thanks to Dr John Munro and Associate Professor John Lucas for their supervision of this work.

Appendix 1

Growth Analysis Techniques for Giant Clams

(a) A first estimate of the asymptotic size (L_∞) and of the Z/K ratio has been derived by compiling the size frequency distributions of the population in the three main sampling periods and applying the Wetherall (1986) method, as embodied in the ELEFAN 2B program of Brey and Pauly (1986), to the average size frequency distribution. Apart from the smallest sizes (< 100 mm) all clams are fully represented in the samples and can be included in the Wetherall plot. That is, no part of the Wetherall plot is biased by size selection.

(b) The triplets of data, each consisting of the length when measured at time m, (L_m), the length when remeasured at time r, (L_r) and the time interval $r-m$ (in days) between the measurements are compiled for each species, ignoring the fact that some individuals were measured up to four occasions and thus contributed more 'triplets' than individuals measured only once. When more than one triplet was available for individual clams the successive growth sectors were used as opposed to the cumulative growth from the initial size when first tagged.

(c) In order to estimate the length at the point of inflexion of the length growth curve a plot of average size increment (mm/year) against mean size ($(Lr + Lm)/2$) of successive length groups is made, using the complete data set. The annual increments will reach a peak at the size of inflexion and thereafter decline with increasing size. These data can be assembled into an empirical growth curve which will underestimate the true growth to a degree because it assumes linear growth between successive points. At sizes in excess of L_∞ only clams with exceptionally large individual asymptotic sizes will be represented and consequently the apparent asymptotic size will be a substantial overestimate of the true average value. Note that the plot is of the *mean* increment in successive size-classes. Thus it is not a Gulland and Holt (1959) plot, which would be based on individual increments.

(d) The preinflexion phase of growth is assumed to conform with the Brody (1945) equation

$$L_t = Ae^{K^1 t}$$

For animals of length L_m at time of marking, m, and length L_r at time of remeasurement, r,

$$A = L_m/e^{K^1 m} = L_r/e^{K^1 r}$$

therefore

$$L_r/L_m = e^{K^1 r}/e^{K^1 m}$$

therefore

$$\log_e(L_r/L_m) = K^1 (r - m) \qquad \ldots \text{Eq. 1}$$

and a plot of the value of $\log_e (L_r/L_m)$ against $r-m$ should give a straight line of slope K^1. The value of the constant A in the Brody equation can only be calculated by reference to the length of clams of known age.

(e) After eliminating all triplets referring to small clams in the preinflexion phase of growth, a check can be made for any suspect measurements by arbitrarily setting the value of L_∞ at $1.02L_{max}$ and applying the equation of Munro (1982) to individual triplets of data. The basic equation, derived from the von Bertalanffy equation is

$$K = (\log_e (L_\infty - L_r) / (L_\infty - L_m)) / (r-m) \quad \ldots \text{ Eq. 2}$$

Triplets which show highly aberrant values of K are reexamined. A measurement error is often indicated in a clam remeasured on two or more occasions if a very low value of K is followed by a very high value or vice versa. Additionally, highly aberrant values of K can be produced by Eq. 2 when L_r and L_m are close to L_∞. This is because small measurement errors can be significant relative to actual growth increments. The consequences of measurement errors on estimates of K are also amplified if the time interval, $t_r - t_m$, is short. In practice a period of 100 days has been adopted as a minimum time between measurements. Triplets yielding values of K greater than two standard deviations from the mean are then eliminated from the data set.

(f) This final data set is then processed using the Fabens (1965) method and estimates of L_∞ and K are obtained. If required, Eq. 2 can then be used to derive final estimates of individual values of K for triplets in which $L_r < L_\infty$. If $L_r > L_\infty$ the method is inapplicable.

(g) Where two or more measurements have been made on individual clams it is possible to apply either the Fabens method or a program developed by D. Pauly (called ETAL1) to obtain estimates of L_∞ and K for individual clams and thus obtain some insight into natural variation in the growth parameters.

Growth and Chemistry of the Shells of Juvenile *Tridacna gigas*

S. Suzanne M. Mingoa* and Colin C. Shelley**

Abstract

The influence of light on shell growth of juvenile *Tridacna gigas* was investigated by rearing juveniles at different light intensities: unshaded, 50% shaded and 90% shaded ambient light. Although there were no differences in shell length, there was a significant difference in shell mass (ANOVA $P < 0.05$) between clams grown under different light regimes, over a period of 10 weeks. The same effect is seen in the opacity of shells from different light regimes. Chemical analysis of shells from unshaded and 90% shaded ambient light regimes determined the weight percent of Ba, Ca, Fe, Mn, Mg, Si and Sr, which did not vary significantly (ANOVA, $P > 0.05$) between shells from different light regimes.

THE influence of light on shell deposition has been studied in several bivalve species. The oyster *Crassostrea virginica* grown in unshaded environments produces a firm shell with green radial markings, whereas in shaded conditions the shell is chalky and its pigmentation changes to a brownish hue (Medcof and Kerswill 1965). Stromgren (1976a) observed that several species of mussels have light- and dark-coloured shells when grown in shaded and unshaded conditions, respectively. He attributed this difference to the presence of pigments in their mantles.

It has been shown that in the giant clam *Tridacna maxima*, the animal derives 50% of its metabolic energy requirements from photosynthetically fixed carbon products from its symbiotic zooxanthellae (Trench et al. 1981). However, whilst light is a major factor controlling tissue growth in tridacnid clams, as yet there is no evidence to indicate a relationship between light and calcification levels.

This study aims to examine shell growth in juvenile *T. gigas* grown under different light intensity regimes, and their comparative shell chemistry.

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Methodology

Acclimation to Light Regimes

Four-month-old *Tridacna gigas* juveniles that had been cultured at the Orpheus Island Research Station (OIRS) were reared for 10 weeks in different light-intensity regimes: unshaded, 50% shaded and 90% shaded ambient light. Shading was achieved using shade cloth. Irradiance was measured at noon on several clear days to determine the actual light reduction produced by these shade cloths. The measurements showed close approximation to the desired levels of light intensity.

Animals were placed in 0.8-l plastic containers. All were aerated and had 1-μm filtered and UV-treated seawater (FSW) running at a flow rate of 1.5 l/hour. The experiment was maintained in a large water bath of running water to minimise large fluctuations in daily water temperature.

The clams were randomly divided into nine groups of 50 clams, and each treatment replicated three times. At the conclusion of the experiment, shell lengths and corresponding dry shell weights (± 0.01 mg) were measured. A dissecting microscope with a micrometer eyepiece was used to measure size.

Electromicroprobe Analysis

Shells of clams that were grown in unshaded and 90% shaded ambient light regimes were analysed for chemical composition. One valve from each clam shell from each treatment was embedded in resin. This was then cut in two along the line of maximum valve inflation through the umbo, using a variable-speed precision saw fitted with a diamond-tipped wafering blade. One half of each block from every valve was then hand-polished flat on a glass sheet using 600 and 1000 grade silicon carbide grits. The surface was then washed and dried prior to sticking to a slightly frosted glass microscope slide. A section about 1-2 mm thickness was sliced from the specimen using the same saw. The thick section was highly polished using silicon carbide and then aluminium oxide polishing powder (1 μm particles). The polished sections were coated by sputtering with a layer of carbon (thickness 200 Å) to ensure good conductivity. The shell sections were then examined using wavelength dispersive spectrometry on a Jeol JXA-840A Electronmicropobe Microanalyser (EMA). The elements probed for were barium, calcium, iron, manganese, magnesium, silicon and strontium. The weight percent (W%) of each mineral oxide was measured at four randomly chosen spots on the inner shell layer of each section.

Data were analysed using a one-way nested ANOVA regression analysis and comparison of simple linear regression equations.

Results

The average initial shell length from a representative sample was 5.75 mm (SD = 0.20). Final shell lengths were: 8.62 mm (SD 0.49) under unshaded ambient light, 8.91 mm (SD 0.32) in 50% shaded conditions, and 8.62 mm (SD = 0.14) in 90% shaded conditions. From pooled values, shell length increased at an average rate of 0.042 mm/day. Measurements of linear shell growth did not vary significantly between clams grown at different light intensities (ANOVA, $F_1 = 1.31$, (2,371)df, $F_2 = 1.11$, (6,371)df, $F_3 = 2.0$, (1,371)df, $P > 0.05$).

The log-transformed values of shell length and dry shell weight are shown in Fig. 1. Correlation was high for all treatments. A comparison of the linear regression lines shows that the regression lines had similar slopes ($F = 0.24$, (2,216)df, $P > 0.05$), but the elevations of the intercepts were significantly different ($F = 43.94$, (2,216)df, $P < 0.05$). The above analyses indicate that the clams differed significantly in the rate of shell deposition with minimal shell deposition at 90% shade, maximum under no shade, and intermediate values at 50% shade. This supported the observation that the opacity of the shells from different treatments was markedly different (Fig. 2).

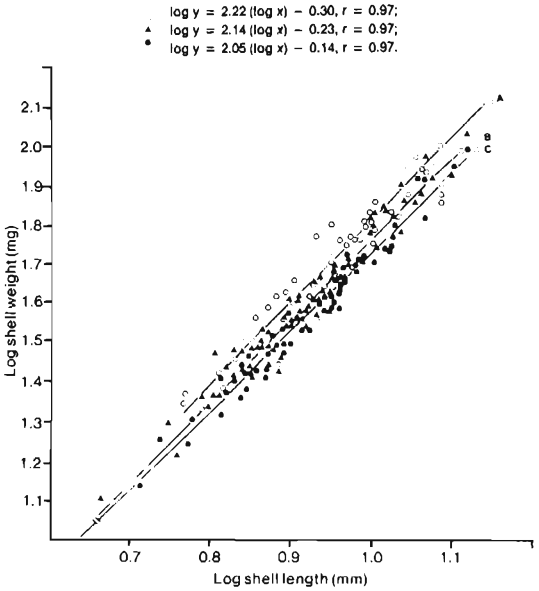

Fig. 1. Regression lines of log-transformed values of dry shell weight against shell length of juvenile *T. gigas* grown in unshaded (open circles), 50% shaded (solid triangles), and 90% shaded (solid circles) conditions.

Electronmicroprobe analysis showed no significant chemical differences (ANOVA, $F_1 = 0.16$, (2,84)df, $F_2 = 0.23$, (2,84)df, $P > 0.05$; $F_3 = 1494.24$, (12,84)df, $P < 0.05$) between shells from unshaded and 90% shade treatments. Table 1 shows the average W% of pooled values of each element for unshaded and 90% shaded treatments.

TABLE 1. Chemical composition of shells of juvenile *T. gigas* grown in unshaded and 90% shaded ambient light regimes.

	Weight % element oxide	
Element	No shade Mean (SD)	90% shade Mean (SD)
Ba	0.045 (0.040)	0.048 (0.055)
Ca	44.390 (2.552)	45.120 (3.566)
Fe	0.098 (0.036)	0.063 (0.032)
Mg	0.003 (0.007)	0.012 (0.013)
Mn	0.058 (0.021)	0.047 (0.034)
Si	0.001 (0.003)	0.003 (0.005)
Sr	0.175 (0.042)	0.166 (0.032)

Discussion

The shell of tridacnid clams is calcium carbonate, in the form of aragonite (Taylor et al. 1973). If changes in shell opacity were related to chemical differences, a change in the calcium composition of

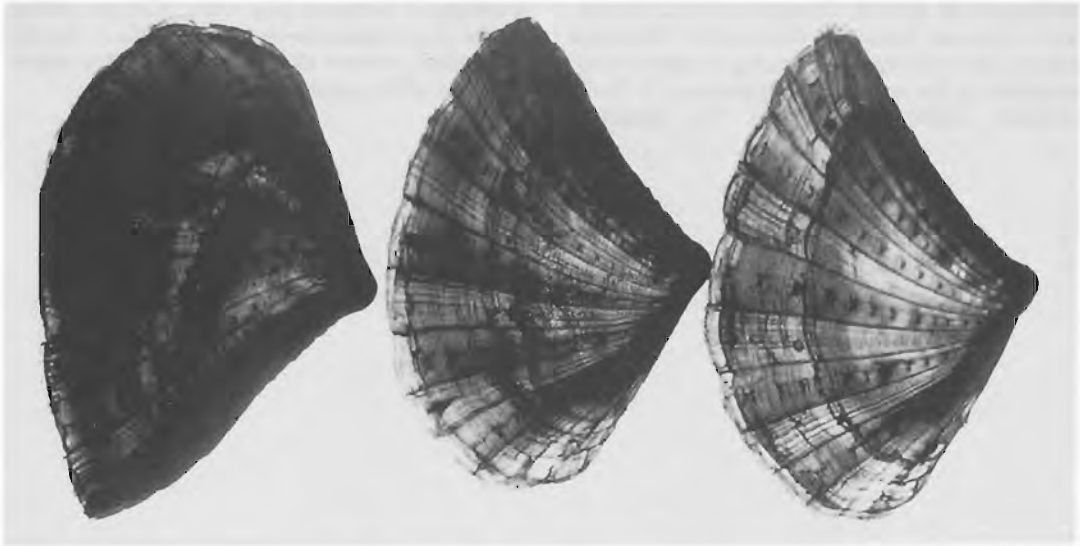

Fig. 2. Half-shells of clams grown at different light regimes: *left*, no shade, *centre*, 50% shade, *right*, 90% shade.

the shells would have seemed most likely. Although there were no significant differences in the W% (oxide) calcium between shells of different opacity, compared to the shell of an adult *T. gigas* (W% (oxide) calcium = 61%) (Shelley unpublished data), there was noticeably less calcium in the juvenile shell (Table 1). This supports the findings of Vinogradov (1953) and Zolatarev (1974) who found an increase in calcium concentration with age in mollusc shells.

This study showed that low light intensities modified shell growth in juvenile *T. gigas*, producing shells that were thinner and less opaque. Seed (1969) observed that *M. edulis* kept in darkness also had thinner shells. Stromgren (1976a) suggested that light possibly controls the deposition of calcium carbonate which follows electrochemical processes as suggested by Digby (1968). Stromgren (1976b) also proposed that biochemically active pigments present in the periostracum, which are capable of absorbing light energy, may influence these electrochemical processes. The role of periostracal pigments in light-induced calcification in junvenile *T. gigas* is still unknown.

Growth in shell size was not affected by different light intensities. This was similarly observed by Mingoa in a subsequent study (unpublished data). However, this finding did not conform to previous observations on other bivalves. Medcof and Kerswill (1965) reported that linear shell growth in *C. virginica* and *M. edulis* increased by approximately 1.5 times when grown in reduced light.

In order to gain an understanding of the influence of light on shell growth in tridacnids, the possible role of their symbiotic algae in calcification needs to be investigated. That increasing light intensities induced juvenile *T. gigas* to produce thicker shells may suggest the greater availability of energy sources obtained from zooxanthellae for the animal to allocate to basal metabolism, tissue and shell growth. It has been shown that a high light regime increases the photosynthetic efficiency of zooxanthellae, resulting in the fixing and translocation of more carbon products to the host, and hence favouring better tissue growth (Mingoa, This Monograph).

The determination of light regimes that may enhance growth is important in the mariculture of giant clams. As discussed by Mingoa (This Monograph), shade cloths have been used to control the growth of filamentous algae overgrowing the small juveniles which are reared in shore-based tanks. In the present study, it was shown that shade cloths also affect shell growth in juveniles, giving rise to thinner, less opaque shells. These results emphasise the importance of the use of condition indices (Lucas and Beninger 1985) which utilise mass as a component for assessing growth, in addition to measuring shell length, which alone may often miss subtle differences in growth performance.

Acknowledgments

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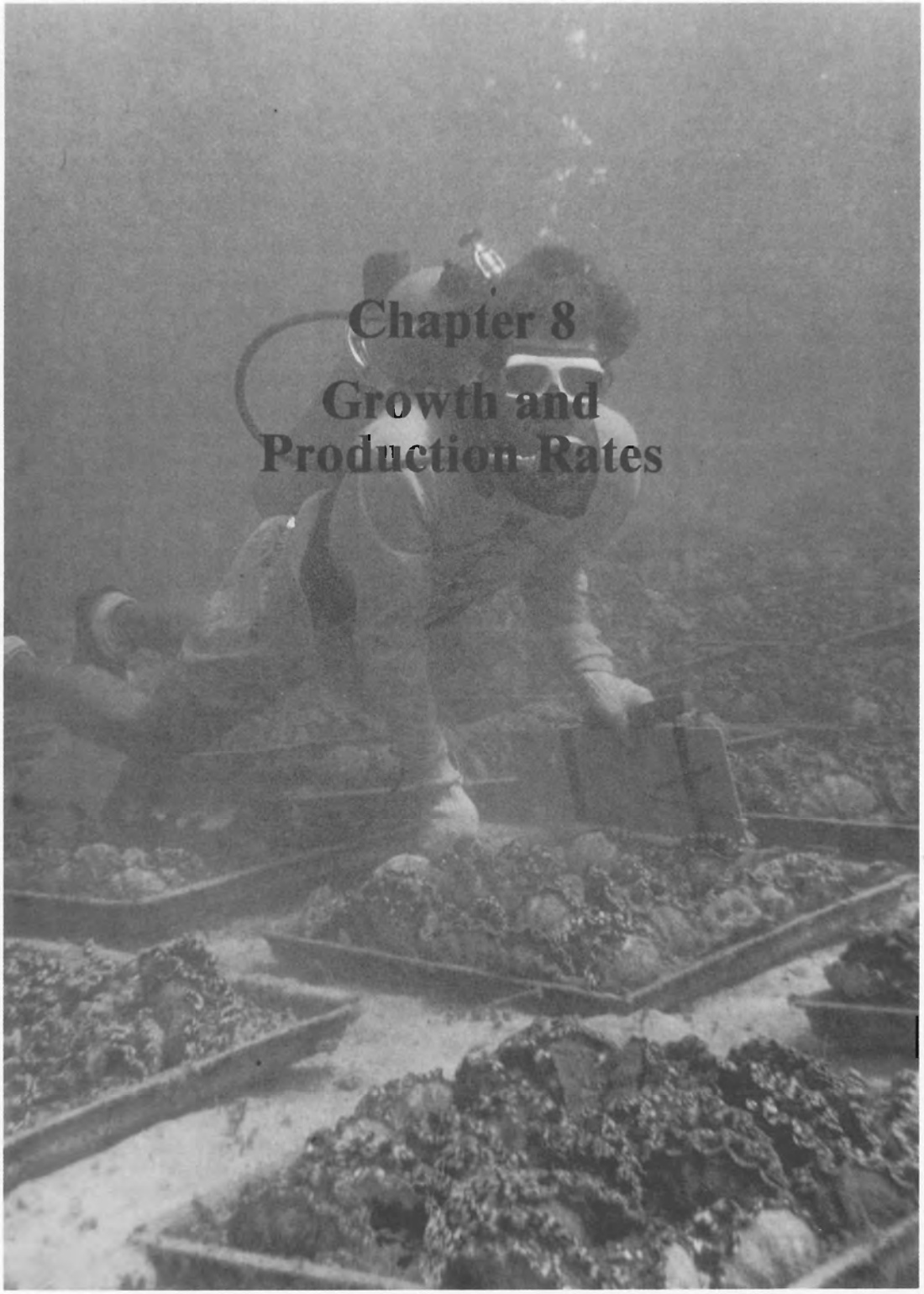

Chapter 8
Growth and Production Rates

Growth, Mortality and Potential Aquaculture Production of *Tridacna gigas* and *T. derasa*

John L. Munro*

Abstract

Comparison of aquaculture production potentials of *Tridacna gigas* and *T. derasa* based on growth and mortality measurements at Michaelmas Reef, northern Great Barrier Reef, show that *T. gigas* will produce a substantially greater biomass per unit time. Selecting the most rapidly growing half of a cohort of spat and culling the slower-growing half could lead to spectacular increases in the biomasses attainable by *T. gigas*.

BOTH *Tridacna gigas* and *T. derasa* are the subject of extensive research at the present time. Both species show clear potential for aquaculture, but little is known of the comparative growth and mortality rates which would govern their potential productivity in aquaculture systems.

Recently, Pearson and Munro (in press) completed an analysis of a large set of data pertaining to *T. gigas* and *T. derasa* at Michaelmas Reef on the Great Barrier Reef. The data set comprises information on stocks of tagged clams monitored over an 8.3-year period. The largest body of information pertains to *T. gigas* but there are also adequate data for *T. derasa*, and it appears to be the first occasion that these two species have been studied at a single location, thus permitting direct comparison of their production parameters.

Previous estimates of growth and mortality rates in adult clams were summarised by Munro and Gwyther (1981) and Munro and Heslinga (1983). Heslinga et al. (1986) and Heslinga and Watson (1985) give data for growth and mortality of cultivated *T. derasa* in Palau. Most recently, Adams (1988) has presented growth rate estimates for *T. derasa* in Fijian waters.

Growth in aquatic animals is conventionally described in terms of the von Bertalanffy growth function (VBGF)

$L_t = L_\infty (1 - e^{-K(t-t_0)})$, in which

K = the coefficient of growth,

L_∞ = the average size towards which individuals in the population are growing.

t_0 = the theoretical date of birth and

L_t = the size attained at time t.

The analyses of Pearson and Munro (in press) show that growth of *T. gigas* is highly variable, with the growth coefficient, K, varying in individual clams by as much as 75% above and below the mean, while the asymptotic size, L_∞, varies by over 25%. This enormous plasticity in growth rates is presumably genetically based, although elements of the symbiotic relationship might also be involved. It was also possible to establish size-specific survival rates for *T. gigas* at Michaelmas Reef.

Productive Potentials

Tables 1 and 2 show computations of the biomasses potentially attainable by cohorts of 10 000, 2-year-old *T. gigas* and *T. derasa* under the conditions prevailing at Michaelmas Reef (16°S lat).

Three sets of estimates are presented for *T. gigas*, based on the average growth and on one standard deviation of the growth performance index, ϕ^1, above and below the mean. The growth performance index is calculated as

$$\phi^1 = \text{Log}_{10} K + 2 \text{Log}_{10} L_\infty$$

(Pauly and Munro 1984).

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TABLE 1. Computations of biomasses attained by cohorts of 10 000 *Tridacna gigas* after periods of 1–10 years, based on growth and mortality estimates for stocks at Michaelmas Reef, Great Barrier Reef. Computations are based on the average growth and on the best (+1 standard deviation) and poorest (−1 standard deviation) growth rates. Parameter estimates derived from Pearson and Munro (in press).

	Years after stocking with 10 000, 2-year-old clams										
Average Case	0	1	2	3	4	5	6	7	8	9	10
$0^1 = 2.83$: $K = .105$: $L_\infty = 80.00$: $t_0 = .145$											
Average individual length (cm)	14.16	20.72	26.63	31.95	36.74	41.05	44.93	48.43	51.58	54.41	56.96
Average individual weight (kg)	.54	1.79	3.95	7.02	10.90	15.46	20.55	26.02	31.73	37.55	43.38
Annual survival rate		.505	.635	.745	.825	.875	.915	.945	.955	.96	.96
Number of clams surviving	10000	5050	3207	2389	1971	1725	1578	1491	1424	1367	1312
Biomass (t)	5.41	9.06	12.68	16.77	21.48	26.66	32.43	38.80	45.18	51.33	56.93
Poor Growth											
$0^1 = 2.70$: $K = .083$: $L_\infty = 80.00$: $t_0 = .145$	0	1	2	3	4	5	6	7	8	9	10
Average individual length (cm)	11.35	16.79	21.79	26.40	30.65	34.56	38.15	41.47	44.52	47.33	49.92
Average individual weight (kg)	.27	.92	2.10	3.85	6.16	8.99	12.28	15.96	19.96	24.20	28.62
Annual survival rate	0	.45	.53	.65	.72	.8	.86	.88	.91	.94	.94
Number of clams surviving	10000	4500	2385	1550	1116	893	768	676	615	578	543
Biomass (t)	2.70	4.16	5.02	5.97	6.87	8.02	9.43	10.78	12.27	13.99	15.55
Good Growth											
$0^1 = 2.96$: $K = .15$: $L_\infty = 80.00$: $t_0 = .145$	0	1	2	3	4	5	6	7	8	9	10
Average individual length (cm)	19.43	27.87	35.13	41.38	46.76	51.39	55.37	58.80	61.76	64.30	66.49
Average individual weight (kg)	1.47	4.56	9.46	15.85	23.30	31.37	39.69	47.96	55.96	63.54	70.60
Survival rate		.54	.77	.88	.93	.94	.95	.96	.96	.95	.94
Number of clams surviving	10000	5400	4158	3659	3403	3199	3039	2917	2801	2661	2501
Biomass (t)	14.66	24.64	39.35	58.00	79.28	100.33	120.60	139.90	156.72	169.05	176.56

TABLE 2. Computations of biomasses attained by cohorts of 10 000 *Tridacna derasa* after periods of 1–10 years, based on growth and mortality estimates for the stock at Michaelmas Reef, Great Barrier Reef (Pearson and Munro in press) and observations in Palau reported by Heslinga et al. (1986) and Heslinga and Watson (1985).

	Years after stocking with 10 000 2-year-old clams										
Michaelmas Reef	0	1	2	3	4	5	6	7	8	9	10
$0^1 = 2.38$: $K = .108$: $L_\infty = 46.90$: $t_0 = .19$											
Average individual length (cm)	9.87	13.66	17.06	20.12	22.86	25.32	27.53	29.51	31.29	32.89	34.32
Average individual weight (kg)	.11	.36	.79	1.43	2.25	3.25	4.37	5.61	6.91	8.26	9.61
Annual survival rate		.505	.635	.745	.825	.875	.915	.945	.955	.96	.96
Number of clams surviving	10000	5050	3207	2389	1971	1725	1578	1491	1424	1367	1312
Biomass (t)	1.12	1.81	2.54	3.41	4.44	5.60	6.90	8.36	9.84	11.29	12.62
Palau											
Empirical growth records											
Average individual length (cm)	10.00	15.00	20.00	25.00	27.50	no estimates available					
Average individual weight (kg)	.12	.50	1.40	3.10	4.36	no estimates available					
Annual survival rate		.9873	.9873	.9873	.9873	no estimates available					
Number of clams surviving	10000	9873	9748	9624	9502	no estimates available					
Biomass (t)	1.18	4.95	13.63	29.85	41.41	no estimates available					

The parameters of the length-weight relationship, $W = aL^b$, are $a = 0.0128$ and $b = 3.15$ for *T. gigas*, when weight (W) is expressed in grams and length (L) in centimetres (Munro 1985). Figures given by Heslinga and Watson (1985) indicate values of $a = 0.0318$ and $b = 3.569$ for *T. derasa*.

The mortality rate estimates derived from Pearson and Munro (in press) show that under the conditions at Michaelmas Reef, survival rates in *T. gigas* rise steadily from negligible levels in the smallest clams to a maximum of about 96% per year at a length of around 60 cm and thereafter decline, presumably as a result of senility of larger individuals. Mortality rates are clearly size-related in the younger stages and fast-growing clams can therefore be expected to have better prospects of survival to a large size. That is, the mortality rates can be expected to be inversely related to growth rates.

The biomasses likely to be attained by the cohorts of 10 000, 2-year-old *T. gigas* differ strikingly (Fig. 1). While an unsorted cohort might attain a biomass of about 27 t, including shells, at 7 years of age, a cohort composed of the slowest growers (one SD less than the mean) would only attain 8 t, while a cohort consisting of faster-than-average growers

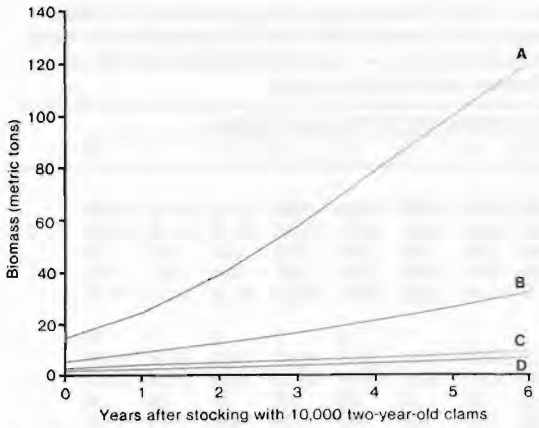

Fig. 1. Calculated biomasses attainable by cohorts of 10 000, 2-year-old giant clams at Michaelmas Reef on the Australian Great Barrier Reef, based on observed growth and mortality rates. Curves shown are for (A) *Tridacna gigas* with faster-than-average growth performance; (B) *T. gigas* with average growth performance; (C) *T. gigas* with less-than-average growth performance; and (D) *T. derasa* with average growth.

would attain over 100 t. The differences are exacerbated by the lower survival expected in slow growers.

Less detail is available for *T. derasa* on Michaelmas Reef but there are estimates of average growth rates available from elsewhere. No details on individual variability are currently available for any area but are expected to emerge from the data recently gathered in Fiji by Dr T. Adams and co-workers. For Michaelmas Reef the parameters of the VBGF are $K = 0.108$, $L_\infty = 46.9$ cm and $t_0 = -0.19$ year (Pearson and Munro, in press). These are close to the values of $K = 0.134$ and $L_\infty = 47.3$ estimated in Fiji (Adams 1988) and $K = 0.132$ and $L_\infty = 50$ cm for Tonga (Munro and Heslinga 1983). Estimates for Palau of $K = 0.187$ and $L_\infty = 50$ cm (recalculated by Munro and Heslinga (1983) from data of Beckvar (1981)) suggest faster growth, possibly reflecting the more tropical situation of Palau compared with the countries mentioned above. However, the sample size was not large. Heslinga et al. (1986) indicate that an average size of 27.5 cm is reached in 6 years by *T. derasa* under cultivated conditions in Palau. This is almost 5 cm larger than this species was estimated to attain in 6 years at Michaelmas Reef. However, slow growers are culled from the cultured stock at Palau.

Heslinga et al. (1986) indicated that they expect 40% survival between stocking into farms at 2 years and harvest at 6 years. The *T. derasa* at Michaelmas Reef were projected to have only 20% survival in the same period. This projection is based on the assumption that the *T. derasa* stocks would follow an age-related pattern similar to that of *T. gigas*. The basis for this assumption is that in the 8.3-year study at Michaelmas Reef the average mortality rates were similar.

The biomass attainable by *T. derasa* under conditions prevailing at Michaelmas Reef is substantially less than that attainable by *T. gigas* (Fig. 1). When survival and growth rates are as great as those reported for *T. derasa* in Palau (Table 2) the resultant biomass will be much larger than that obtained from an unselected, unprotected wild cohort. However, this will be less than that attainable by the fastest growing components of a cohort of *T. gigas*. If the survival rates attained in Palau for *T. derasa* can be emulated the potential production per cohort of cultivated *T. gigas* might be almost an order of magnitude greater than that attained by a wild cohort.

Conclusions

It is concluded on the basis of this comparison that *T. gigas* offers a greater productive potential for mariculture than *T. derasa* by virtue of its superior growth rate, its weight at a given age being about five times greater than that attained by *T. derasa*. However, the survival rate between stocking and harvest is also a critical element in the maricultural process and has a very large effect on the final biomass. In order for *T. gigas* to be superior in terms of productive potential a survival rate is required of at least one-fifth of that attained by *T. derasa*. This would appear to be an attainable objective but quantitative data are not yet available on survival rates in cultivated *T. gigas* stocks. It is also evident that the opportunities for developing faster-growing strains of giant clams are of great importance and should not be ignored.

Optimal Harvest Age for *Tridacna derasa*: Maximising Biological Production

T.C. Watson and G.A. Heslinga*

Abstract

Analysis of size-at-age data from a cohort of cultured *Tridacna derasa* indicates that where maximum biomass production is the objective, optimum age at harvest is as follows: for adductor muscle, 6 years; for other soft tissues, 6 years; and for shell, more than 7 years.

GIANT CLAM mariculture technology has progressed to the point where laboratory-spawned cohorts of *Tridacna derasa* are being reared to sexual maturity on a routine basis (Heslinga et al. 1984; Heslinga and Watson 1985; Heslinga 1988; Heslinga and Fitt 1987). It is now possible to begin a quantitative assessment of the question: 'What is the best time to harvest cultured specimens?' The answer is complex and depends on whether one wishes to maximise biological, economic, social or ecological returns. In this article we restrict our analysis to optimal harvest age from a biological perspective. We ask: 'What harvest schedule permits the farmer to maximise average annual production of biomass per unit area?'

Yamaguchi (1977) was the first to recognise that forest management techniques might be useful in managing tridacnid clam resources. One relevant approach concerns the 'biological rotation' or harvest age of a crop, at the point of maximum volume or biomass production. The rotation of maximum biomass production is defined as 'the rotation that coincides with the age at which the mean annual increment culminates and hence yields the most material per unit per area per annum' (Ford-Robertson 1971). Mean annual increment (MAI) or mean annual growth is 'the total increment (growth) up to a given age divided by that age' (Ford-Roberston 1971):

MAI = Total growth (year x)/Age(year x).

Periodic annual increment (PAI) is the net growth during a given period divided by the time span of that period:

PAI = Net growth during the period/Years in the period.

According to Avery (1975), 'Periodic annual growth increases rapidly, reaches a crest, and then drops off rapidly. Mean annual growth increases more slowly, attains a maximum at a later age, and falls more gradually. When curves of periodic annual growth and mean annual growth are plotted over age, they intersect at the peak of mean annual growth. This culmination point for mean annual growth is regarded as the ideal harvesting or rotation age in terms of most efficient volume production.'

Harvesting when PAI is greater or less than the MAI reduces annual yield per unit area. In general, the point of maximum biomass production occurs earlier at better sites, which have faster growth rates.

Results

Size-at-age data for a cohort of *Tridacna derasa* specimens spawned in Palau in 1979 (Heslinga 1988; Heslinga et al. 1984; Heslinga and Watson 1985) are presented in Table 1. This is the most comprehensive data set presently available for cultured tridacnids. In Tables 2, 3 and 4 calculations of MAI and PAI are given for three commercially important variables: adductor muscle weight, other soft tissue weight, and shell weight. Figures 1–3 show MAI and PAI curves for these body components, and Fig. 4 illustrates age-weight relationships for *T. derasa*.

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TABLE 1. Age, size and weight of maricultured *Tridacna derasa* (from Heslinga 1986).

Shell length (mm):	50	100	150	200	250	275	300
Approximate age (years)	1	2	3	4	5	6	7
Shell dry weight (g)	5.3	106	390	964	2800	3730	4833
Adductor muscle weight (g)	-	0.83	13.7	26.6	65.1	81.7	81.0
All other soft parts weight (g)	-	11.0	79.3	146	388	535	613

TABLE 2. Mean annual increment (MAI) and periodic annual increment (PAI) for adductor muscle in cultured *Tridacna derasa*.

Year	Weight (g)	MAI (g)	Period	PAI (g)
1	0.1	0.10	0–1	0.1
2	0.8	0.41	1–2	0.7
3	13.7	4.56	2–3	12.9
4	26.6	6.65	3–4	12.9
5	65.1	13.02	4–5	38.5
6	81.7	13.62	5–6	16.6
7	81.0	11.57	6–7	-0.7

TABLE 3. Mean annual increment (MAI) and periodic annual increment (PAI) for soft tissues other than adductor muscle in cultured *Tridacna derasa*.

Year	Weight (g)	MAI (g)	Period	PAI (g)
1	1	1	0–1	1
2	11	5.5	1–2	10
3	79	26.4	2–3	68
4	146	36.6	3–4	67
5	388	77.6	4–5	242
6	535	89.2	5–6	147
7	613	87.6	6–7	78

TABLE 4. Mean annual increment (MAI) and periodic annual increment (PAI) for shell in cultured *Tridacna derasa*.

Year	Weight (g)	MAI (g)	Period	PAI (g)
1	5	5	0–1	5
2	106	53	1–2	100
3	390	130	2–3	284
4	964	241	3–4	574
5	2800	560	4–5	1836
6	3730	622	5–6	930
7	4833	690	6–7	1103

Optimal harvest age for maximum biological production of a given component is indicated by the intersection of its MAI and PAI curves. Thus, optimal harvest age for adductor muscle is 6 years (Fig. 1), for other soft tissues 6 years (Fig. 2), and for shell, greater than 7 years (Fig. 3). The optimal harvest age for maximum shell production in cultured *T. derasa* cannot yet be determined precisely because even at age 7 years, MAI is still increasing.

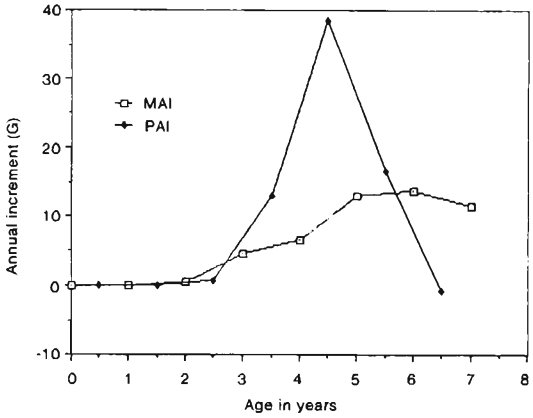

Fig. 1. Annual growth increment for muscle. (MAI = mean annual increment; PAI = periodic annual increment).

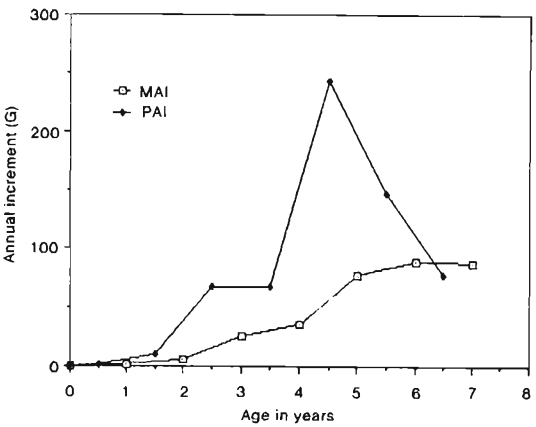

Fig. 2. Annual growth increment for other tissues.

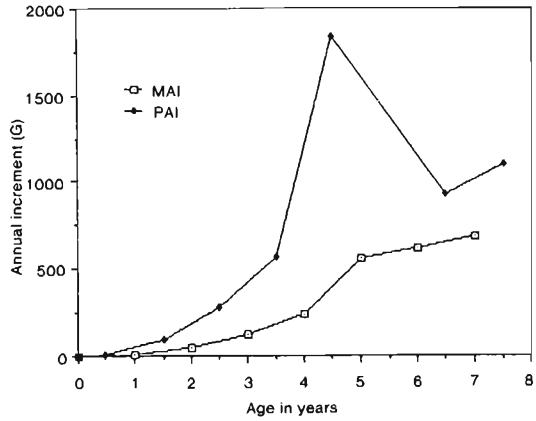

Fig. 3. Annual growth increment for shell.

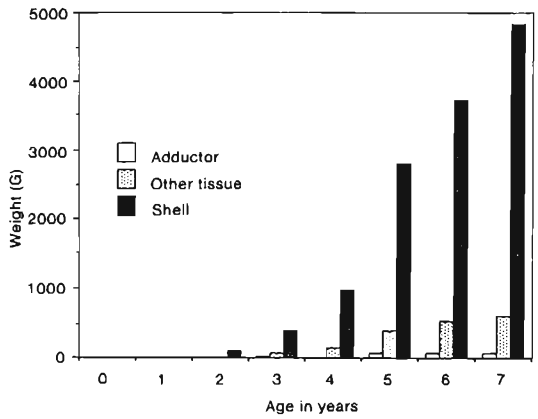

Fig. 4. Shell and tissue weight vs age.

Discussion

It is important to stress that for a given species and a given body component, MAI, PAI and optimal harvest age may vary with cohort and culture regime. Even within a narrowly defined geographic area, factors such as water temperature, salinity, clarity, depth, nutrient availability and current speed vary among microhabitats and can be expected to influence growth rates. Temporal or seasonal factors may also be significant. Moreover, in the future the mean growth performance of individual cohorts may improve as a result of better rearing methods and artificial selection. In short, MAI and PAI curves should be regarded as species-specific, component-specific, site-specific and cohort-specific, and subject to recalculation as the need arises. In spite of these limitations, the present analysis is valuable as a first order approximation.

Harvesting at the age of maximum biological production is just one of several options available to the tridacnid clam farmer. It is of obvious importance if food production is the primary goal. Other strategies might stress economic return, stock enhancement, conservation, or some combination of objectives. For example, tridacnid hatcheries targeting the market for seed might harvest their product at an age of 1 year or less, while farmers supplying the sashimi trade or the aquarium trade might harvest specimens at about 1–2 years of age.

For conservation-oriented programs, harvest should be delayed until after the onset of reproductive maturity at age 5 years (Heslinga et al., This Monograph). *Tridacna derasa* specimens spawn repeatedly between ages 5 and 6. Therefore, farmers harvesting *T. derasa* at age 6 would achieve two objectives: maximising adductor muscle

production and contributing to future recruitment of juvenile clams in the natural environment.

There is a need to extend the results presented here to other tridacnid species and to other marine habitats in the Indo-Pacific region. The present paper is of value because it provides a straightforward and proven method for analysing cohort growth data. The conclusions can be viewed with more confidence than those resulting from methods which require excessive statistical manipulation.

Acknowledgments

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Ocean-Nursery Technology and Production Data for the Giant Clam *Tridacna gigas*

J.R. Barker, C.M. Crawford, C.C. Shelley, R.D. Braley, J.S. Lucas, W.J. Nash and S. Lindsay*

Abstract

Five devices for the protection of cultured juvenile giant clams (*Tridacna gigas*) in the ocean-nursery phase were investigated. These were known as trays, boxes, lines, covers and exclosures. The emphasis was a gradual reduction in the material cost and maintenance, and an increase in the size. The merits of each design were assessed. Clams at 0.83, 2.0, 2.6 and 3 years were dissected and the wet tissue mass, shell mass and total mass recorded. From these data the potential production from the ocean-nursery phase was calculated. A survival rate of 40% from the lines and covers for the period covering clams aged 6–8 months to 3 years was obtained. This was used for the calculation of potential production figures. A general figure of 29 t/ha of wet tissue was calculated.

JUVENILE clams (*Tridacna gigas*) rapidly outgrow the area in which they settle in the onshore nursery tanks. It is necessary to harvest them from the tanks and distribute at a lower, uniform density to maintain the space around each clam and thus sustain rapid growth. One option is for them to be placed into additional tanks. However, this can become expensive due to the material cost, land space required and seawater pumping cost. It is therefore most economical to transfer the juveniles to the ocean-nursery stage, consisting of protective containers on the reef flat, at the smallest size possible.

The design conditions and requirements of the ocean-nursery phase for giant clams have been discussed by Munro (1985), Heslinga et al. (1986) and Lucas et al. (This Monograph). One of the primary considerations is the protection of juvenile clams from predation. Predators on the Great Barrier Reef include large tusk fish, parrot fish, octopus, rays, crabs and molluscs such as bailers, cone shells and oyster borers. Different sizes of clams are susceptible to predation from different organisms, and thus the degree of protection required varies for each stage of clam growth. Any design must also be based on a consideration of the ease of construction, maintenance and operation as well as cost. The ocean-nursery system must be relatively inexpensive to construct and maintain if the operation is to be commercially viable.

This paper describes the ocean-nursery protective containers that have been developed and tested at Orpheus Island over the last 2 years. Some estimates of production of clams from the ocean-nursery stage are also given.

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Protective Containers

Prawn Trays

The first group of clams transferred to the ocean-nursery system was placed in perforated plastic trays (prawn freezer trays 550 × 300 × 90 mm) and covered with black Nylex 26-mm plastic mesh. They were placed mostly in the subtidal zone on the reef flat, and an experiment was conducted to assess several culture methods for the ocean-nursery phase (Crawford et al. 1988). The prawn trays were satisfactory for growing the juvenile clams, however

the cost per unit clam was relatively high because of the material and labour required for construction and maintenance. Thus a larger unit of simpler construction, called a 'box,' was tested.

Boxes

Boxes were made from galvanised steel mesh of 100-mm mesh size lined with plastic (12 or 26 mm) mesh. Overall length was 1.9 m, width 0.9 m and height 0.2 m (Fig. 1). Each box was situated on cement blocks about 30 cm off the bottom and anchored to the substrate using star pickets and electrical wire. It was filled with coral rubble or stone chips, to a depth of approximately 40 mm, to act as ballast and a substrate for the clams to attach to.

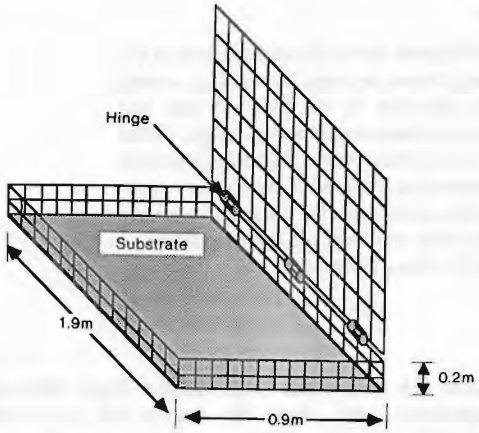

Fig. 1. Protective box for juvenile clams.

Lines

The next level of protection to be tested was much larger than the boxes, easier to construct and costs per unit clam were substantially less. Lines were 30 m long and 1.1 m wide. These dimensions are based on the maximum which could be obtained from a commercially available roll of plastic mesh. Each line was divided by 12 mm plastic mesh into cells at 2.0-m intervals. The base and sides were made from 5 mm or 12 mm plastic mesh and the lid from 26 mm plastic mesh. Each cell had a lid that could be opened separately from its neighbour although the whole structure was wired together. Galvanised steel fencing wire running the complete length of both sides of the line and anchored at intervals by star pickets was used to support the structure. An artificial substrate of coral rubble or stone chips was placed in the lines for clams to attach to (Fig. 2).

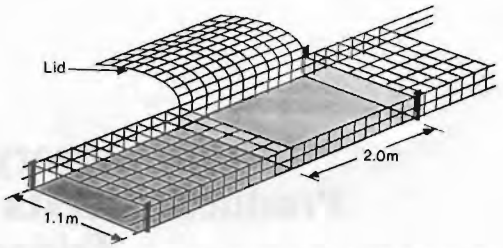

Fig. 2. Protective line showing individual cell — 15 cells/line.

Covers

A structure known as a 'cover' was constructed and tested as protection for larger juvenile clams. Its design was similar to the lines except there were no internal divisions and no base. The clams were allowed to rest directly on the reef flat. Plastic mesh (40 × 60 mm mesh size) was placed over the clams with approximately 1.1 m wide base. Access into the cover was via 18 V sections cut in the top at regular intervals. These were normally wired shut (Fig. 3).

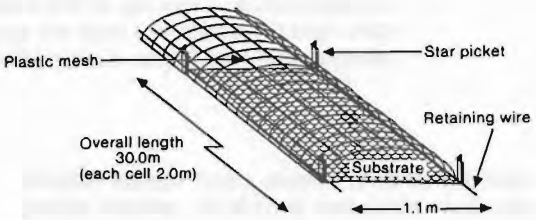

Fig. 3. Protective covers showing overall design.

Exclosures

An 'exclosure,' a much simpler and cheaper protective device primarily for larger juvenile clams, was tested next. This was basically a fence made of 25 mm plastic mesh and anchored to the reef flat by galvanised fencing wire and star pickets. It had a maximum height of 4 m and was kept upright by floats set along the upper edge. The lower edge had a 200 mm skirt pointing outwards and held in place at frequent intervals by large coral boulders. Each side was 15 m long and formed a square. At each corner there was a guy rope for stability and a large buoy to act as a major float and marker. The clams were placed directly onto the reef flat where they anchored themselves using their byssus. Demarcation lines were set at 3 m intervals which enabled the monitoring of clams in 25 individual cells.

These protective containers have been developed as the juvenile clams increased in size and required

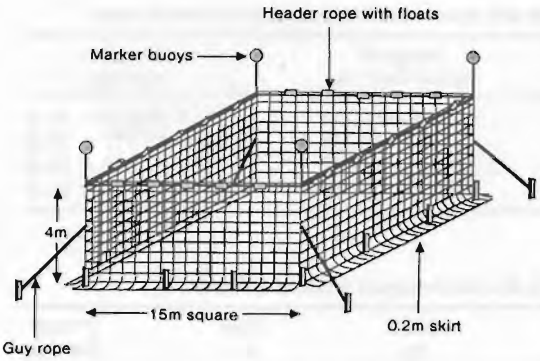

Fig. 4. Exclosure for the protection of juvenile clams.

a larger surface area of substrate to prevent overcrowding. The emphasis has been on producing a protective container which was less costly per unit clam but still provided adequate protection for each size class. Trays, boxes and lines which offered the greatest protection from small predators, due to the small mesh size, have generally been used for small juveniles which have come directly from the onshore-based nursery facility.

It is envisaged that in future, lines will be used predominately for small juveniles because they provide adequate protection and are much cheaper than trays and boxes. The lines also do not become fouled from sessile organisms and algae as frequently as boxes due to the smaller area available for attachment. However, the structure is susceptible to breakage under heavy seas as was noted during storm conditions in February 1988. One lid was removed for much of its length during a 2-day period of up to 2-m high waves.

So far there has been no serious damage to the covers and they appear more suitable for the protection of clams above 2 years old, which represents the age at the time of their transfer, usually from lines. The major cause of mortality for clams under this type of protective device is from predation by octopus. A single octopus can, in a few nights, kill 15 or more clams. Two-year-old clams have recently been established within an exclosure with the intention of growing through to harvestable size without being disturbed. The exclosure needs to be trialled for a longer period of time before its suitability as a protective container can be compared with covers. However, the major disadvantage of an exclosure is that if predators manage to get inside they have access to a very large number of clams.

Survival

Survival in the lines was dependent on age at the start of the experiment and the period of time in the container (Table 1). Predation in the lines was limited but mortality, especially in the earlier stages of growth, appeared to be due to other causes such as algal overgrowth. The mortality reduced with increasing age and for clams from 20 months of age survival was greater than 82%. The major causes of mortality for clams at this age was due to overcrowding, resulting from insufficient thinning, or gear failure which allowed access for larger predators such as tusk fish *Choerodon* sp. or octopus. At 3 years old they are essentially immune to attack and mortality was negligible as the results of leaving clams of this age unprotected on the reef flat have shown.

Mortality in the lines and covers cannot be directly compared because of the difference in age of the clams in each. The covers generally did the necessary job of protecting clams older than 2.5 years, however, deaths to octopus can be a regular occurrence if one becomes resident near the covers. Clams of this age and older have high survival rates (Table 2); 90% survival under covers is not unexpected.

In the ocean-nursery system an overall survival of 41% was obtained over a period of 19 months for clams that were 11 months old at the beginning of the tests (Table 1). Since mortality is normally low for clams 2.5 years and older, a 40% survival appears valid for the period from 6 to 8 months at the time of the movement to ocean-nursery culture, to one possible harvest age of 3 years.

Production

Clams 0.8, 2.0, 2.7 and 3 years old (n = 20, 20, 10, 10 respectively) were dissected to establish the

TABLE 1. Mean measurements for cultured *T. gigas* of different ages.

Age (years)	Length (cm)	Shell mass (g)	Wet tissue mass (g)	Total wet mass (g)	Wet tissue mass (% of total)
0.83	18.6	0.474	0.066	0.54	12.2
2.0	121.1	152.1	41.62	193.72	21
2.66	206.4	694.2	229.05	923.25	24.8
3.0	221.3	862.6	304.9	1152.8	26

TABLE 2. Survival of *T. gigas* for different time periods and ages within the lines in the intertidal zones.

Spawning date	Age at start (months)	Period in lines (months)	Range of initial/final no.	Percent survival
Oct. 85	11	19	338–568/123–273	31.5–55.5 ($\bar{x}$ = 41.3)
Jan. 86	16	11	180/133–157	73.9–83.3 ($\bar{x}$ = 78.6)
Jan. 86	20	7	100–120/ 88– 98	73.3–97.0 ($\bar{x}$ = 82.6)
Jan. 86	22	5	100–150/ 90–150	90.0–100.0 ($\bar{x}$ = 93.5)

TABLE 3. Survival of clams under covers in the ocean-nursery phase of culture.

Cover	Age at start (months)	Period in covers (months)	Initial no.	Final no.	Percent Survival
1	18.5/26.5	10.5	563	533	94.7
2	19	10	943	892	94.6
3	15.5	9.5	953	730	76.6[a]
4	20	9	666	601	90.2
5	17/20	9	700	660	94.3

[a] High mortality due to early attacks from octopus; average for all five covers = 90%, using the best four = 93%.

relationship between age, size and tissue mass. Measurements were made of shell length, shell mass, total wet tissue mass and total wet mass (Table 3).

The likely growth rate for *T. gigas* in the intertidal zone at Orpheus Island is sufficiently fast to produce, in 2.5 and 3 years, a clam between 185 and 221 mm respectively. At this size they will be, on average, between 190 and 305 g wet tissue mass, respectively. However, if the shell is included then the average mass increases to 730 and 1153 g respectively. In the growth period between 2.5 and 3 years there is a 1.6-fold increase in both the wet tissue mass and total wet mass. With age, up to 3 years, there is a progressively greater proportion of the total mass taken up by the tissue. At 0.83 year the tissue mass represents 12.2% of the total mass; at 2 and 3 years old this figure rises to 21 and 26% respectively.

If the average 3-year-old *T. gigas* is 220 mm long × 180 mm wide it would require approximately 625 cm^2 of reef flat for unobstructed movement and growth. Therefore, assuming an initial stocking density of 1000, 6–8-month-old individuals per cell in a line of 15 cells, and a survival rate of 40%, the necessary bottom area required at 3 years would be 375 m^2 (6000 clams). Assuming a maximum ratio of line area to water area of 0.6 as is generally used in the oyster industry (Braley 1984), then these clams would require 625 m^2 of reef flat if they are within a cover or line. If all the stock is 3 years old then there would be 96 000 clams/ha. This would represent 29 t of wet tissue and 110 t total mass (shell and wet tissue)/ha. Although this is not an expected production figure for a commercial operation because of the extra area of reef flat required for the younger clams (assuming a survival rate of 40% there would need to be 250 000, 6–8-month-old clams initially occupying 17 lines covering approximately 925 m^2), it is in accord with the findings of Heslinga and Watson (1985) where they report an expected production figure from a hypothetical farm of 22 t/ha/year for *T. derasa*.

Before further predictions can be made with respect to the possible production from an aquaculture enterprise on the Great Barrier Reef, further work on the average mortalities for the different age-groups and the potential marketable size needs to be completed.

Acknowledgments

We would like to thank all the people involved with the work at Orpheus Island Research Station.

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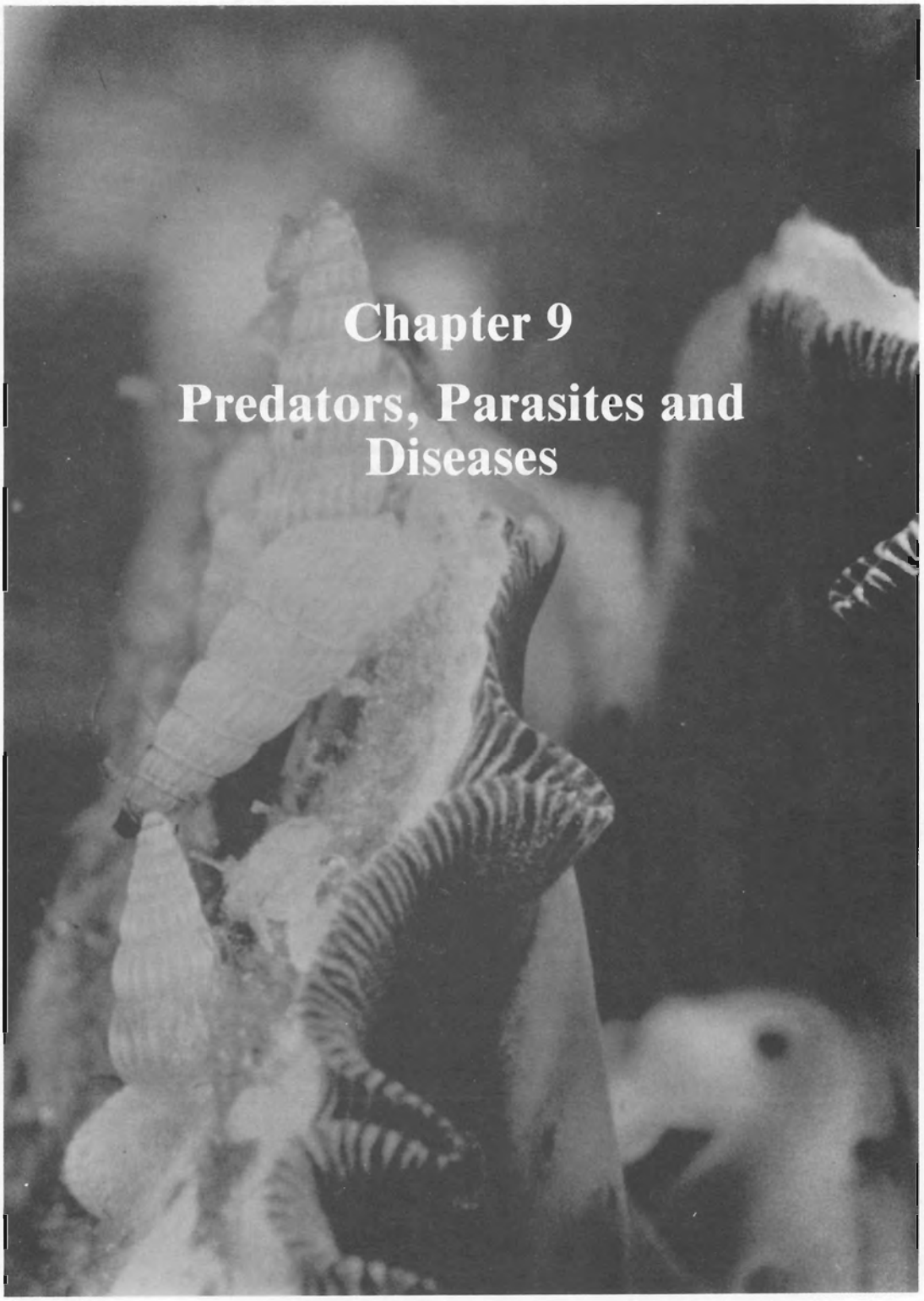

Chapter 9

Predators, Parasites and Diseases

Mass Mortalities of Giant Clams on the Great Barrier Reef

J. Alder* and R.D. Braley**

Abstract

Mass mortalities of giant clams (Tridacnidae) were first reported and confirmed in July 1985 at Lizard Island reefs in the northern waters of the Great Barrier Reef. Initial mortality rates for combined species were 20–30%. Over an 18-month study, total mortality rates were 55–58%. Since the report of Lizard Island reef mortalities other mass clam deaths have been investigated. In 1986 at North Direction Island, south of Lizard Island, there was a 10% mortality rate for *Tridacna* spp. in less than 4 months, and at Thetford Reef 25% of *Tridacna* spp. died within 4 weeks. In 1987 Thetford Reef again experienced a 25% loss of clams. Deaths at Lizard and Thetford were recorded in the winter months, July and August.

Determining the cause of these deaths has been difficult. Tissue samples have been difficult to obtain since dead clams are quickly consumed by predators. Identifying unhealthy clams has not been possible. Shells are quickly fouled and therefore it is difficult to detect mass mortalities that have occurred 2 or 3 months before. However, at Lizard Island reefs tissue samples have been obtained from dead or dying clams: four *Tridacna gigas*, one *T. maxima* and one *Hippopus hippopus* for histopathological studies.

The factors investigated that may be contributing to these deaths were: toxins, predators, environmental conditions, pathogens and old age. Toxins were discounted since the level of heavy metals was similar to healthy clams and no other organisms were dying. Predators were not a likely cause, since the size of clams affected was too large for known predators. Environmental conditions for deaths at Lizard Island and Thetford Reef were low temperatures and low tides in the winter months. However, deaths have been recorded in other months. Two pathogens have been identified in dead or dying clams, *Perkinsus* and an unidentified parasite, possibly a ciliated protozoan. Old age has been discounted as a cause of death since all size-classes were affected and mortality rates were much higher than natural mortality rates at other reefs.

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Pyramidellid Parasites in Giant Clam Mariculture Systems

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Abstract

Current knowledge of the occurrence of pyramidellid ectoparasites in giant clam mariculture systems is reviewed. *Pyrgiscus* sp., which occurs amongst giant clams at Orpheus Island Research Station, was studied. Its feeding and behaviour inside seawater tanks are described. Its life history, reproductive capacity, recruitment and population growth were investigated.

Egg masses are laid on clam shell surfaces. The species has a short free-swimming larval stage, lasting 3–5 days, with veligers hatching about 10 days after spawning. Life-span was about 3 months in seawater tanks. Upon attainment of sexual maturity individuals produced an egg mass once every few days.

Populations grew remarkably fast — within 4 months initial populations of six adults gave rise to an average of more than 1700 individuals. Recruitment in seawater tanks was primarily due to spawn laid by adults within the tanks, rather than larvae entering through the seawater system. Juvenile recruitment is highly aggregated. Greater numbers of new recruits appear on clams with greater numbers of adults. Possible mechanisms for this are considered.

In comparison to the seawater tanks, *Pyrgiscus* populations amongst juvenile *Tridacna gigas* in the ocean-nursery are small. A small portunid crab eradicated a pyramidellid population when three of the crabs were placed in a tank with heavily infested clams. The possibility of using this and other species as biological controlling agents is considered.

THE gastropod family Pyramidellidae is a large family of small, shelled opisthobranchs (Fig. 1). The family has a world-wide distribution and it comprises thousands of species, with probably more than 1000 in the Pacific Ocean alone (Laseron 1959). As far as is known all the pyramidellids are ectoparasites and all feed on the body fluids of their hosts (Fretter and Graham 1949). The hosts are marine invertebrates, most commonly molluscs and polychaetes (Robertson and Mau-Lastovicka 1979).

Current knowledge of the Pyramidellidae is limited. It consists of details of only a small number of species, the majority of which are parasites on commercially important oysters and mussels (e.g. Ward and Langdon 1986; White et al. 1985). I am not aware of any published information on those species which parasitise tridacnid clams. In fact the existence of such species has only become apparent in recent years with the development of giant clam mariculture systems. Infestations have occurred in land-based seawater tanks containing giant clams at the Micronesian Mariculture Demonstration Center (MMDC) in Palau (J. Moore, pers. comm.), the University of the Philippines Marine Science Institute (UPMSI) (M. Trinidad-Roa, pers. comm.), Lizard Island Research Station in Australia (R. Braley, pers. comm.) and the Orpheus Island Research Station (OIRS) in Australia (Crawford et al. 1988). There appear to be at least three different species involved in these infestations. Dr Winston Ponder of the Australian National Museum has tentatively identified the MMDC species as *Tathrella iredalei*, the OIRS species as *Pyrgiscus* sp. and the Lizard Island species is as yet undescribed (J. Waterhouse to J. Lucas, pers. comm. 1987). It is

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Fig. 1. An adult *Pyrgiscus* sp. with proboscis extended, feeding on mantle tissue of a juvenile *T. gigas*.

interesting to note that no such infestations have occurred at Silliman University in the Philippines, where seawater tanks have been operating for 5 years (J. Estacion, pers. comm.).

When left unchecked the pyramidellids have caused mortality of juvenile giant clams in the seawater tanks at OIRS (Crawford et al. 1988) and at MMDC (J Moore, pers. comm.) and in field situations at OIRS where clams have been kept away from the substrate, either on racks or suspended from floats (Crawford et al. 1988; Lucas 1987). However, observations of juvenile clams in the ocean nurseries which are on the substrate at OIRS, MMDC and UPMSI have indicated that pyramidellids are rare or absent in such benthic situations (T. Watson, M. Trinidad-Roa, pers. comm.; Crawford et al. 1988).

At OIRS *Pyrgiscus* is found on *Tridacna derasa, T. squamosa, T. maxima, T. gigas* and *Hippopus hippopus* kept in seawater tanks. Reported here are some preliminary results of a study of *Pyrgiscus* on *T. gigas*. The aims of the study were to investigate (1) the mode of development and dispersal capability; (2) the nature and rate of recruitment onto clams; (3) the rate of growth of populations; and (4) the nature of populations in the ocean nursery.

Methods

Reproduction

Egg masses were removed from the surfaces of clam shells and kept in glass beakers 7.25 cm in diameter and 3 cm deep, at a temperature range of 22–23°C. The water was changed daily. It was possible to observe embryonic development with a high power microscope by transferring the egg masses onto cavity slides with a pipette with no apparent damage.

Preliminary histology revealed that *Pyrgiscus* is a simultaneous hermaphrodite. To measure size-specific fecundity small clams were placed in transparent plastic containers 9 cm in diameter and 10 cm deep. These were floated in raceways with styrofoam frames to allow ease of handling and to prevent pyramidellids from straying between clams. Ten pyramidellids of five different size-classes were placed on one clam in each of five containers. The size-classes were 2–3 mm, 3–4 mm, 4–5 mm and 5–6 mm long. Individuals greater than 6.5 mm were rare. The 2–3-mm size-class was divided into two classes, 2–2.5 and 2.5–3 mm, after the first trial. The number of egg masses produced and the number of eggs per egg mass were counted daily for a period of 3–4 days at intervals of 4–6 weeks.

Recruitment in Raceways

The experimental unit used in recruitment studies consisted of a plastic tray, 60 × 35 cm, with a 24 × 35 cm section divided off with plastic mesh. This section contained three juvenile clams of equal age (spawned in January 1986) and approximately equal size, and a gravel substrate as attachment for the clams. Four replicate trays were used in each treatment.

Three fibreglass raceways were used, each with four replicate trays. A different treatment was applied to each raceway. Initial populations of two pyramidellids per clam were placed in two of the raceways. One of these raceways (A) was provided with a 25-μm filter bag on the inflow pipe to prevent pyramidellid larvae from coming in through the seawater system. Recruitment in this tank was then solely via spawn from the adults already present. The other raceway (B) had no filter bag, thus allowing recruitment through the seawater system as well as from adults already present. The third

raceway (C) was started with no initial populations of pyramidellids so that recruitment into this tank relied totally on larvae coming in through the seawater system, which had no filter. The populations were counted and measured monthly.

After 4 months the experiment was terminated and restarted with treatments in different raceways, to account for any raceway effect. Results from the second trial are not yet available but tentative conclusions can be drawn from the first trial.

Effect of Adult Density on Recruitment

An experiment was conducted on a subtidal rack about 5 m deep and 1.5 m above the substrate to test for the effect of initial pyramidellid density on population growth rate. The experimental unit was identical to that used in the raceways, with the addition of a 2.5-cm wire mesh lid to protect the juvenile clams from fish predation. There were four treatments, consisting of four initial densities of pyramidellids per clam: 0, 2, 10 and 20. Four replicate trays of each treatment were organised on the rack in a randomised block design, with trays distributed randomly within blocks to allow for any effects of tides and currents. The experiment was commenced on 5 September 1987 and the populations were counted and measured on 5 November 1987. One-way analysis of variance was used to test the hypothesis that initial density of pyramidellids on 5 September 1987 had no effect on subsequent density on 5 November 1987.

Pyramidellids in the Ocean Nursery

Juvenile *T. gigas* in the intertidal ocean nursery were sampled three times for pyramidellid populations. In the first sample — at low tide on 23 July 1987 — cells containing different age-groups of juvenile clams were selected randomly and five clams were randomly sampled within these cells. Sixty-five clams were sampled, including three different age-classes, spawned in February 1985, October 1985 and January 1986.

The second sample was taken on 31 March 1988 at high tide in the morning and the third sample was taken on the same day on the following high tide after dark. In both cases five clams were selected randomly from each of 10 cells containing clams of equal age — all spawned in January 1986.

Control of Infestations in Tanks

A small portunid crab commonly found amongst trays of clams placed on the substrate was identified as *Thalamita sima* H. Milne Edwards (Stephenson and Hudson 1957). Only small specimens (1–1.5 cm across the carapace) were found amongst the clams, although they grow to a maximum size of 2.5 cm. They fed on large numbers of pyramidellids when kept in an aquarium and, as a result, an experiment was designed to examine their ability to control pyramidellid numbers in the seawater tanks. One raceway at OIRS was divided in half with 5 mm plastic mesh. Each half was stocked with three juvenile *T. gigas* (spawned January 1986) with populations of 30 pyramidellids per clam. Three small *T. sima* individuals were added to one half and the experiment was sampled 1 month later.

One specimen of *T. sima* was subsequently offered 10 juvenile clams (mean size 2 mm diameter) as food.

Results

Feeding and Behaviour

Pyrgiscus displays a diurnal pattern of behaviour. In the seawater tanks during the day they remain either on the tank floor directly beneath clams or on the lower half of the clam shell where they are shaded from direct sunlight. At night they crawl up to the lip of the clam to feed. After positioning at the shell edge, the proboscis is extended slowly and steadily out from the mouth and over the edge of the shell until it contacts the mantle flesh. The feeding action can be observed as rhythmic contractions of the buccal pump at the distal end of the proboscis (Fig. 1).

Pyrgiscus aggregated amongst clumps of macroalgae attached to the surface of clam shells, particularly the filamentous types. Aggregations of pyramidellids were often found partially or completely concealed by the algae, along with embedded egg masses and, on many occasions, dense concentrations of small (< 1 mm) juveniles.

Pyrgiscus is quite mobile and will move readily between adjacent clams when placed on them artificially. However, once established they appear to remain associated with a particular host. The parasite secures itself to the host by means of a fine but strong 'attachment thread' which can be stretched to several times the length of the animal before breaking.

Reproduction

Egg masses are laid day and night and are correspondingly found on lips or bases of clam shells. They are also, less frequently, found on the substrate. They are transparent, irregularly shaped, jelly-like lumps 2–4 mm in diameter. The clear jelly in which the egg capsules are embedded causes them to adhere to one another and attaches them firmly to the substrate. All egg masses on one clam are often close together.

Egg capsules are 0.40 ± 0.05 mm long and 0.30 ± 0.04 mm wide. Size is uniform within egg masses and constant between egg masses laid by individuals of different sizes. The number of eggs in an egg mass

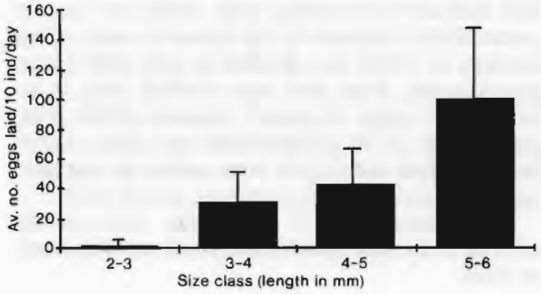

Fig. 2. Size-specific fecundity for four size-classes (means for all sampling times November 1987 to April 1988). Vertical lines represent 95% confidence limits, here and in Fig. 3.

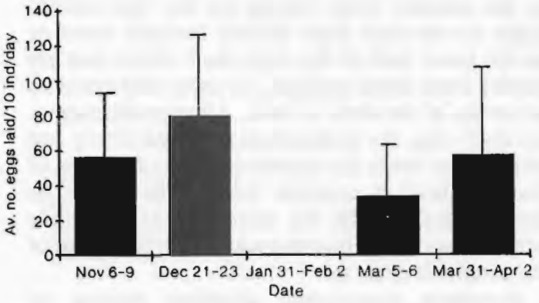

Fig. 3. Variation of fecundity with time (means for all size-classes combined).

varied between 3 and 226, but was normally between 20 and 120 ($\bar{x}$ = 43 ± 36; n = 148). After 7 days development the embryos are actively swimming veligers inside the egg case. After 8–9 days they have a fully developed larval shell into which they can contract fully. The veligers hatch after about 10 days into free-swimming larvae. In glass beakers the larvae spent much of their free-swimming time retracted into their shell or crawling over the substrate, and only swam actively when their container was agitated. They could not be induced to swim 3–5 days after hatching and appeared to have lost the velum. They crawled actively over the substrate and were presumed to have metamorphosed.

Fecundity increased with size (Fig. 2). This was due mainly to increased number of eggs per egg mass, rather than increased number of egg masses laid. Division of the smallest age-class of 2–3 mm into two classes showed that size of sexual maturity was 2.5–3 mm, although regular egg production only occurred amongst animals 3–4 mm and larger. The 10 individuals of the larger three size-classes produced an average of 2–3 egg masses/day. This indicates that a mature individual lays an egg mass every few days.

Fecundity varied over time although the variation was not significant (see Fig. 3). The greatest egg production occurred in December. No eggs were laid by any size-class in the February trial. This coincided with the time of highest water temperatures at OIRS — mean temperature in land-based tanks was greater than 30°C.

Recruitment in Raceways

Size-frequencies for all sampling dates for the three raceways are shown in Fig. 4. In raceways A and B (those with initial populations) two new generations appeared within 4 months. The new November cohorts grew rapidly, reaching near maximum size by December, and virtually disappearing by January. This indicates a life-span of about 3 months, at least for this time of year. In raceway C no recruitment through the seawater system occurred for the first 2 months until December, when two pyramidellids had recruited to the same clam. Once a population was established in raceway C there was rapid population growth, with the appearance of a new cohort by January. The entire population was within one tray — the other three replicates contained no pyramidellids at all. This showed aggregated recruitment of juveniles.

These results indicate that by far the greatest source of recruitment of pyramidellids into seawater tanks at OIRS is from the spawn of those already present, rather than from larvae entering through the seawater system. Once an initial population is established, population growth is rapid. By December initial populations in raceways A and B had multiplied by a factor of 17. By January, there was a further 7–10-fold increase. Replicate populations in raceway B grew from 6 to a mean of more than 1700 in 4 months. Population size in January in raceway B was much larger than in raceway A but until results of the second trial are available it is not possible to attribute the difference to presence/absence of a filter preventing input of larvae from outside.

Effect of Density on Recruitment

The mean population sizes for each treatment in September vs November were 0 vs 17.6, 6 vs 94.3, 30 vs 591, and 60 vs 766. The effect of initial density of *Pyrgiscus* is highly significant ($P < 0.01$) and it accounts for 86% of the variation in the data (R^2 = 0.856). Hence the hypothesis that initial density of pyramidellids at 5 September 1987 had no effect on subsequent density at 5 November 1987 is rejected. This means that recruiting larvae were not settling randomly amongst clams but were highly aggregated, with greater numbers of new recruits where there were greater numbers of adults.

Of the 48 clams used in this experiment 18 had

died by 21 December 1987; 16 of these were in trays with initial densities of 10 or 20/clam.

Pyramidellids in the Ocean Nursery

In comparison to the land-based seawater tanks, pyramidellids were relatively rare in the ocean nursery, especially in March 1988.

Biological Control

In the divided raceway, the half containing no *Thalamita sima* contained healthy populations of pyramidellids, with an average of 17 per clam. The half containing *T. sima* contained no live pyramidellids. Sieving debris from this tank revealed many small fragments of broken pyramidellid shells.

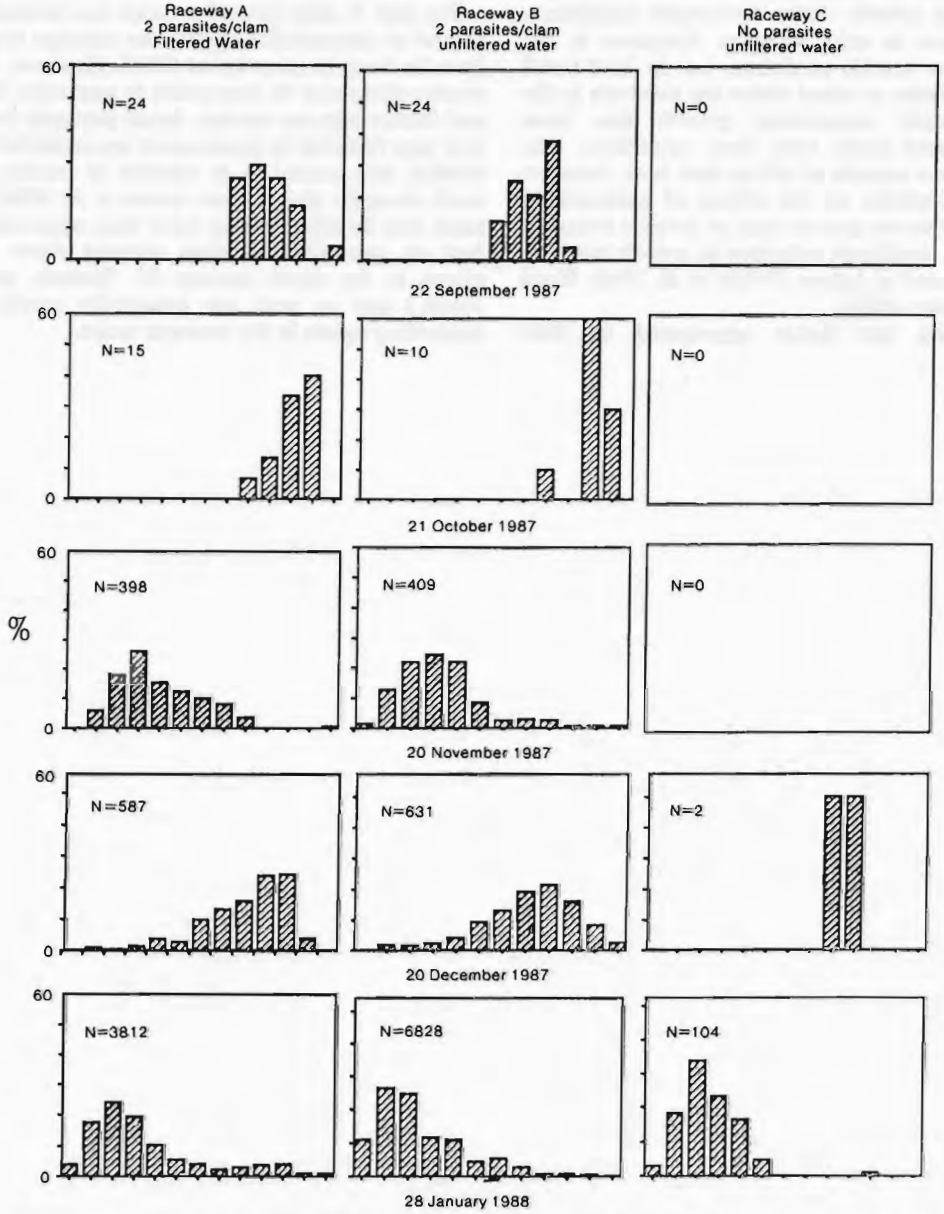

Fig. 4. Size-frequencies for each raceway on each sampling date: the size-classes represent intervals of 0.5 mm.

The crabs therefore appear to be an effective control mechanism. The individual to which 2 mm juvenile clams were offered showed no interest in feeding on these. However, the clams offered were considerably smaller than pyramidellids and may have been too small for the crab to eat. Unfortunately, no larger juvenile clams were available at the time.

Discussion

Pyrgiscus is capable of remarkably rapid population growth under favourable conditions, which seem to exist wherever *Pyrgiscus* is not exposed to benthic predators, i.e. in land-based seawater tanks or raised above the substrate in the field. Rapid population growth has been demonstrated under both these conditions. The parasites are capable of killing their host. Data are not yet available on the effects of pyramidellid parasitisation on growth rates of juvenile tridacnid clams but significant reduction in growth has been demonstrated in oysters (White et al. 1984; Ward and Langdon 1986).

Juveniles are highly aggregated in their distribution. It seems most likely that larvae are not swimming away from their clam of origin. Alternatively settlement could be highly selective, with strength of the settlement stimulus being proportional to number of adults present, or there could be highly differential survival of new recruits amongst clams. As a result of such aggregated recruitment, the establishment of as few as only two pyramidellids on a clam is sufficient to initiate massive population growth and lead to the death of a 23-month-old *T. gigas* only 3 months later.

The crab *T. sima* showed promise as a biological control of pyramidellid infestations amongst larger juvenile clams in raceways at OIRS. However, the smaller clams may be susceptible to predation by it and further tests are needed. Small portunid crabs that were found to be predators of pyramidellids at MMDC also proved to be capable of feeding on small clams (J. Moore, pers. comm.). At MMDC, small reef-dwelling wrasses have been observed to feed on pyramidellids when infested clams are placed in the ocean nursery (T. Watson, pers. comm.) and as such are potentially useful as controlling agents in the seawater tanks.

Quarantine Aspects of the Reintroduction of *Tridacna gigas* to Fiji

E. Ledua and T.J.H. Adams*

Abstract

As part of the reintroduction of *Tridacna gigas* to Fiji, strict quarantine measures were undertaken to lessen the risk of introducing diseases and parasites. Hatchery-grown juveniles, rather than adults, were chosen, and were held under rigid quarantine at Dalice on the island of Makogai. This site is now used as an animal quarantine and breeding station. The clams were moved to ocean-nursery cages after 6 months, and growth and survival have been satisfactory.

RESULTS of surveys from 1984–87 throughout Fiji waters have shown that the largest and most commercially important of the species of tridacnids, *Tridacna gigas*, is no longer found in Fiji. The evidence for its former presence is limited firstly to one reliable report of a live specimen (the shell of which can be seen in Suva) being fished at Wailagilala, a remote atoll in the Northern Lau Group, during the course of lighthouse maintenance work in 1970, and secondly to the fact that there is a Fijian name, *vasua matau*, attributed to *T. gigas*. Several other shells can be seen in suburban gardens, but none of these have been traced, although some are rumoured to come from Vatulele, a low limestone island with a shallow lagoon to the south of Viti Levu. Rosewater (1965) includes Fiji in the geographic range of *T. gigas*, although without supporting specimens.

However, no specimens, alive or dead, have been found in the water during the course of Fiji surveys by the ACIAR Giant Clam Project and it is likely that *T. gigas* was never particularly common here on the edge of its geographical range. Its large size and its probable habitat near the larger islands would make it vulnerable to exploitation. It will prove instructive in the future to examine the fossil record and shell-middens.

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The Fiji Module of the ACIAR Giant Clam Project made the decision to reintroduce *T. gigas* to Fiji in order to have the option of eventually mariculturing this fast-growing species. It was considered preferable to introduce hatchery-grown juveniles rather than adult individuals, to lessen the risk of introducing diseases and parasites. The project also considered this a useful test of the feasibility of setting up quarantine systems for the reintroduction of giant clams to small Pacific islands in general.

Site

The quarantine system is at Dalice on the northeast side of Makogai, a small (9.6 km^2) volcanic island in the Koro Sea. Makogai has an extensive barrier reef and Dalice Bay is further sheltered by the island of Makodroga to the north. The bay is usually full-salinity, since there is very little freshwater runoff, and water clarity generally good. There are few giant clams to be seen in Dalice Bay, as it is comparatively well populated and a good anchorage, but *T. derasa, T. squamosa* and *T. maxima* can be found around the island and on the barrier reef. There are also many fossil tridacnid shells to be seen along the shore, and historical shell-dumps on the south side of the island.

Dalice is the site of a former leper colony, and Makogai is now used as an animal quarantine and breeding station by the Ministry of Primary Industries. Existing, but in some cases derelict,

infrastructure was available for use by the clam project, and government casual workers helped with the construction work.

The Fisheries Division hopes to turn the Makogai barrier reef and lagoon into a marine reserve. The first step is to secure ownership of the fishing rights, but the taking-over of traditional ownership is likely to be a controversial matter in modern Fiji. It may be possible at some future date to lease marine spaces, and several useful precedents are being set at the present time.

Seawater System

Dr C. Crawford, who was then with the International Giant Clam Project in Townsville, assisted with the initial design for the pumping system, after visiting the site in 1986.

There are two seawater pumping systems at Makogai. The main pump is a CP1600 Mono electrical pump with a pumping capacity of 7500 l/hour. The standby pump is a WA20X Honda fuel pump with a pumping capacity of 600 l/min. Each pump is plumbed separately into the system through different header tanks and filters. Since the electrical system on the island has not yet been upgraded, the Honda pump was in operation during the entire quarantine period (Fig. 1) and a second fuel pump had to be brought in to act as backup.

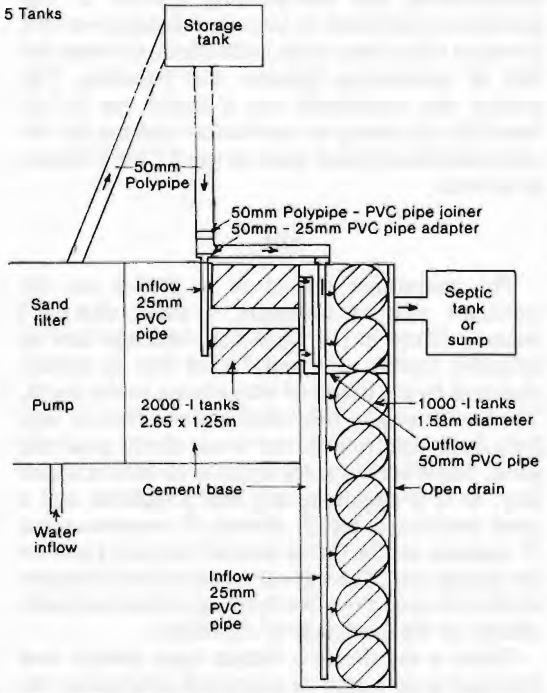

Fig. 1. Quarantine system for giant clam juveniles at Makogai Island.

The intake line is made of 50-mm polyethylene pipe and runs 65 m out from high water mark to the edge of the fringing reef. The foot-valve is approximately 2 m underwater at low tide.

An existing 25 000-l concrete rainwater tank was converted into a storage header tank. From the storage tank, a 50-mm PVC pipe gravity-feeds seawater into 5 × 1000-l and 2 × 2000-l fibreglass tanks. The 50-mm PVC pipe is reduced to 25 mm before it feeds into the quarantine tanks and 25-mm gate valves are connected to each inflow pipe to regulate seawater flow. Centre 50 mm standpipes drain seawater from the quarantine tanks into a closed septic tank 20 m from the shore, so there is no direct outflow into the lagoon.

Due to the high flow rate of the Honda pump, it was only necessary to run the pump twice a day, for 1 hour at a time, to keep the header tank topped up. With the tank capacity in use at the time this meant that the water was turned over in the quarantine tanks about 6 times every 24 hours.

Quarantine

The first test of the system was in September 1986, when approximately 2000 juvenile *T. gigas* were sent from the Orpheus Island hatchery (James Cook University of North Queensland). The spat were first 'pre-quarantined' in UV-irradiated seawater for several weeks. After a sample was examined at the Australian Government Laboratories for harmful organisms, the clams were put into plastic bags with a little seawater and an oxygen atmosphere, and sent by boat, car and finally air to Fiji. Unfortunately the oxygen had escaped from the bags by the time they arrived, and the water was discoloured and cloudy. Total travel time was less than 24 hours. After a day in the quarantine tanks at Makogai, the clams looked as though they might recover, but within a week all had died. Several locally captured *T. squamosa*, acting as controls in a separate tank, showed no signs of distress.

The second shipment of 475 juvenile *T. gigas* was received on 17 February 1987. This time the clams were older (5–6 cm) and were double-bagged with prominent warnings about the danger of opening the bags. After arrival (26 hours in transit) they were released into 5 × 1000-l fibreglass tanks as described earlier.

A filter bag of 25 μm was used on the inflow pipe of each quarantine tank and the outflow from each tank was channeled into a drain which flowed directly into a septic tank. Filtering the inflow of quarantine tanks is almost as important as filtering the outflow, otherwise if diseases or parasites occur in quarantine it will not be known whether they are introduced or locally acquired.

Tanks were cleaned every 2 weeks. Silt and algae

were removed from tank bottoms by siphoning. Observations on juveniles were carried out daily. Water temperature, weather conditions, mortality and possible causes of mortality were recorded each day for 6 months.

Unhealthy-looking specimens were closely observed and the byssal orifice and mantle areas were searched for the presence of predatory gastropods. Individuals which lost mantle pigment, or showed a slow closure reflex were normally placed in a separate tank. In practice, many of the juveniles which developed grey patches on the mantle recovered their pigment within a week or two. Such grey mantle areas (presumably due to the loss of zooxanthellae) have also been observed many times in natural populations of *T. derasa*. Is this a harmless phenomenon or a symptom of malaise?

No pyramidellids, or indeed any gastropods, were observed in the tanks throughout the quarantine period. At least seven species in the family Pyramidellidae have been recorded from Fiji (B. Parkinson, pers. comm.).

Ocean Nursery

After spending 6 months under quarantine, the juveniles were released into ocean-nursery cages in Dalice Bay. The cages went through various designs and placements in an effort to control the high mortality that occurred in the lagoon.

By a process of trial and error it was discovered that:

- cages should be raised above the substrate to help prevent predatory gastropods getting in easily, and to reduce sediment deposition on silty bottoms;
- cages should either be large, or corners tied down securely to prevent storm-waves washing the cages away;
- mesh-sizes should be large enough to prevent algal fouling. Algae grow better in shallow water, but intertidal placement of cages will reduce algal overgrowth. However, intertidal cages are too easily disturbed by curious fishermen.

At present, the remaining *T. gigas* are in 1.5 m × 0.9 m × 15 cm cages at 3 m depth (at low tide) on the sandy lagoon floor. The cages are raised on blocks and tied down to star-pickets. The cage mesh is scrubbed to remove overgrowth, and regular 'snail patrols' are made. *Cymatium muricinum* is definitely present and has been observed in one cage, and *Chicoreus ramosus* has been observed elsewhere in the lagoon.

Mortality

Of the 475 juveniles that were received from James Cook University, 419 survived the quarantine period. Total mortality within the 6-month period was 11.8%. Nearly half of the total mortality was experienced in the first week when 24 died, and 22 of these died during the first 2 days of quarantine. Mortality rates were then negligible until week 10 when an average of two juveniles per week died until the end of the quarantine period (Fig. 2, 3).

In sick juveniles, the mantle became white, then shrunken before death. Such specimens were normally removed from quarantine tanks and closely examined for the presence of predatory or parasitic gastropods, always with negative results. Many individuals with bleached mantles subsequently recovered, but these never got to the stage of mantle shrinkage.

The same symptoms have been observed several times in local clams which have been stressed by translocation or by shading. Juvenile *T. gigas* were seen to clump together in the quarantine tanks, and

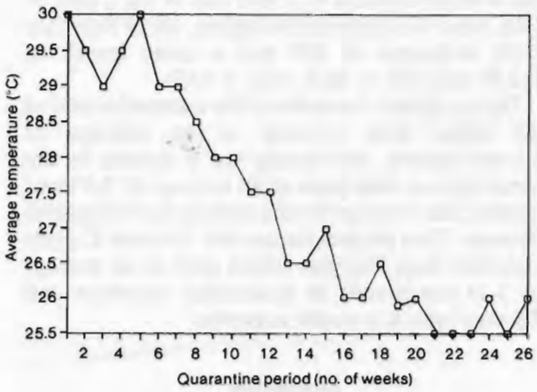

Fig. 2. Temperature range within the quarantine period February–August 1987.

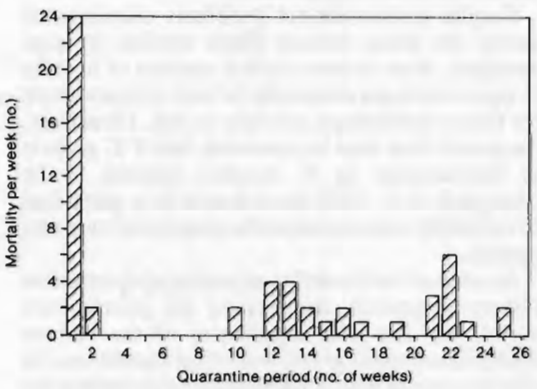

Fig. 3. Mortality during the February–August 1987 quarantine period.

it was concluded that the low, continuous mortality was due to intraspecific competition, rather than parasites or disease.

Mortality during the ocean-nursery stage has been somewhat higher. Part of this was due to unavoidable natural causes (a cyclone in February destroyed over half the remaining stock) and part is due to deliberate experimentation with different habitats (some of which proved to be unsuitable). However, ocean-nursery methods now appear to have been optimised and few losses occurred in early 1988.

Growth

The *T. gigas* juveniles arrived in quarantine on 17 February 1987. They were not measured until 18 May 1987, when 434 individuals had an average length of 79.92 mm (SD = 15.82, max = 123). At the end of quarantine on 12 August 1987, when they were placed in the ocean nursery, a sample of 281 had a mean length of 97.7 mm (SD = 18.7, max = 150). After 6 months in the lagoon, on 29 February 1988, a sample of 267 had a mean length of 113.97 mm (SD = 18.2, max = 155).

During the last 4 months of the quarantine period the clams were growing at an average of 6.2 mm/month, and during the 6 months in the ocean nursery they grew at an average of 2.4 mm/month. This reverses the situation in the Philippines (Gomez, Clam Project Report No. 7) where *T. gigas* imported from Orpheus Island grew at an average of 2.15 mm/month in quarantine raceways and 7.3 mm/month in ocean nurseries.

Discussion

The quarantine system at Makogai had two main purposes: (1) to reintroduce *T. gigas* to Fiji, and (2) to test the feasibility of setting up quarantine systems in small Pacific islands.

Despite environmental problems encountered during the ocean nursery phase leading to large mortality, there is now a sound nucleus of healthy *T. gigas* which can eventually be used as broodstock for future mariculture activities in Fiji. Obviously, the genetic base may be restricted, but if *T. gigas* is as heterozygous as *T. maxima* appears to be (Campbell et al. 1975) there should be a great deal of variability even amongst the progeny of only two parents.

As a test of the feasibility of setting up quarantine systems in general, the exercise has proved very useful, and the joint experiences of the various institutions present at this workshop should now be able to come up with a practical set of guidelines for low-cost but effective quarantine (and later, hatchery) systems.

The main requirements appear to be: (a) a good flow-rate of seawater through the tanks or raceways; (b) filtered inflow; (c) outflow discharging onto land; (d) a backup pumping system to make sure that the flow rate can be maintained at all times; (e) a supply of clean, full-salinity seawater; and (f) someone to maintain pumping operations and check mortality.

The main expense is in the cost of pumping seawater. In Fiji, at least, several island hotels have seawater pumping systems for sanitation, and most hotels would be very interested in having tanks of giant clams on the premises. If the cost of pumping is unavoidable then there are several broad alternatives. If large header tanks are available, as at Makogai, then a high flow-rate, portable petrol pump may be the best option, as this can often be borrowed for a couple of hours a day from another department. If no header tanks are available or if they are considered too expensive, then a low flow-rate diesel or solar pump running full-time is necessary.

Raceways or tanks can be made of almost anything (except preservative-treated timber and epoxy resin fibreglass). Two-metre diameter fibreglass aquaculture tanks were used at Makogai because the Fisheries Division had several available, but the ICLARM Coastal Mariculture Center in Solomon Islands demonstrates a perfectly adequate design composed of four coconut logs and a sheet of thick plastic.

Inlet filtration can be accomplished using ordinary commercial water filters of a small enough pore size, or simply by tying bags of filter cloth over the inlet pipe and making sure they are cleaned regularly.

In summary, quarantine systems are a viable option for most countries. It must be accepted that moving giant clams from one place to another carries the risk of spreading pathogens and parasites, and if such transfers are necessary then as many precautions should be taken as possible. This can include both prequarantine at the hatchery site (in UV-irradiated seawater) and postquarantine at the recipient site (keeping the clams under observation in tanks for up to 6 months). Ideally, such transfers should be considered only as sources of future broodstock. Hopefully, it will soon be possible for each site to perform cheap, effective hatchery operations and restock their own reefs without having to compound the risk with further transfers. A postquarantine setup, such as that described here, contains most of the elements necessary for a hatchery.

Disease Risks Associated with Translocation of Shellfish, with Special Reference to the Giant Clam *Tridacna gigas*

J.D. Humphrey*

Abstract

The translocation of molluscan species is invariably accompanied by the potential to transmit infectious pathogens or undesirable exotic species in or on the translocated molluscs. Numerous well-documented examples are described whereby serious diseases or ecologically undesirable species have established in a new region as a direct consequence of the movement of molluscs between regions. These cases, which have often resulted in catastrophic mortalities or severe ecological imbalances, demonstrate the strict controls which are necessary when considering movements of molluscs, either nationally or internationally. This paper briefly reviews some translocations of molluscs which have concurrently introduced serious diseases in new or susceptible hosts, or have introduced undesirable exotic species into the new environment. Also reviewed are those known diseases and parasites of giant clams (*Tridacna* spp.). Finally guidelines will be presented on which a disease-testing strategy, designed to minimise the risks of inadvertently transmitting infectious pathogens or undesirable exotic species, may be formulated.

THE spectrum of diseases, parasites and ecologically undesirable exotic species that have established as a consequence of movements of molluscs between environments are described in detail by Andrews (1980), Lauckner (1983) and Sparks (1985). It is noteworthy that such agents represent only a small proportion of the described diseases and parasites of molluscs, and of the exotic species with potentially undesirable or unknown effects. Nevertheless, these few agents have resulted in severe socioeconomic losses and environmental degradation where they have established.

Perkinsus marinus (*Dermocystidium marinum*), an acetosporan protozoan, was introduced into Chesapeake Bay, USA, prior to 1940 in oysters (*Crassostrea virginica*) from the Gulf of Mexico, resulting in high mortalities in the local populations.

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Mytilicola intestinalis, a copepod parasite of mussels (*Mytilus edulis* and *M. galloprovincialis*), has been spread by infected mussels throughout Europe and the British Isles since 1939, causing catastrophic mortalities in *M. edulis*. *Mytilicola orientalis*, a parasite of *Crassostrea gigas, M. edulis* and other bivalves, causing poor condition and metaplastic changes, was introduced to North America, and more recently France, in seed oysters from Japan. Severe epizootics of disease with high mortalities occurred in native oysters following importation of oysters from New England to Malpeque Bay, Canada, beginning in 1915. Malpeque Bay disease has since spread widely and is still present. The causative agent is unknown.

Minchinia nelsoni, a haplosporidian parasite of oysters, was believed to have been introduced to Delaware Bay, USA, in 1957 in imported oysters. This agent resulted in deaths of half the oyster beds in New Jersey within 6 weeks and later caused epizootics in Chesapeake Bay. In all more than 90%

of oysters in both bays in salinity >15 ppt were killed within 2 years. *Bonamiasis*, a disease of oysters (*O. edulis*) caused by the haplozoan-like protozoan *Bonamia ostreae*, has been widely disseminated through European oyster-growing areas by the movement of infected oysters. Aber disease of oysters (*O. edulis*) caused by *Marteilia refringens* has resulted in high mortalities in France following introduction of Pacific oysters (*C. gigas*). As a final example, a disease affecting gills of the oyster *Crassostrea angulata*, resulting in high mortalities, spread widely in France during 1966–67. This disease was associated with the importation of oysters from Japan.

The propensity by which harmful exotic species are spread concurrently with molluscan translocations is exemplified by the introduction of the predatory oyster drill *Urosalpinx cinerea* into England in oysters *(C. virginica)* from North America. *Urosalpinx cinerea* is now a major cause of economic losses on oyster and mussel beds. This species also attacks other motile bivalves. A gastropod competitor *Crepidula fornicata*, which grows in explosive populations on oyster beds, was introduced in American oysters (*C. virginica*) from North America into England, and is now widely distributed from Sweden to France. The Japanese oyster drill *Ocenebra japonica* is among the most damaging of marine Gastropoda (Lauckner 1980) and is now common on west coast oyster beds in the USA as a result of its introduction in Japanese oysters (*C. gigas*). Finally, a flatworm predator of oysters, *Pseudostylochus ostreophagus*, which causes heavy mortalities in the cultivated oysters *Ostrea lurida, C. virginica* and *C. gigas* (Lauckner 1983), was introduced to the west coast of the USA in oysters from Japan (Andrews 1980; Sparks 1985; Lauckner 1983).

It is important to recognise that the dissemination of the above agents was directly attributable to inadequate health surveillance and specific testing for freedom from pathogens, epiphytes or extraneous species in the populations destined for translocation. Such quarantine and health certification procedures are fundamental to disease control and prevention in vertebrates, and the same principles must be applied to invertebrates when undertaking translocation or restocking procedures.

Diseases and Parasites of Giant Clams

While there is a large body of literature relating to diseases of molluscs in general and bivalves in particular, reports of disease, pathogens or parasites in *Tridacna* spp. are few.

A poorly understood syndrome characterised by epizootic mortalities of giant clams has occurred in northern sections of the Great Barrier Reef, in recent years (Alder and Braley, This Monograph). In a histopathological study of mantle tissue of clams from affected, unaffected and apparently recovered reefs, Humphrey (1987) found evidence for morphological differences in zooxanthellae populations between clams from different locations, with possible inhibition of mitotic activity and the development of small zooxanthellae in affected locations.

An unidentified ciliated protozoan which invades the mantle and apparently ingests zooxanthellae is known (J. Glazebrook, pers. comm.) but its pathogenic significance remains obscure. A larval trematode (Family Bucephalidae) infects the gonads, kidney, digestive gland and gills of *T. crocea* on the Great Barrier Reef. Heavily infected clams are castrated (Shelley et al. 1988). Mortalities in larval cultured clams at Orpheus Island have occurred and have been attributed to bacterial infections (Glazebrook 1987).

Perkins (1985) reported *Perkinsus* sp. in *Tridacna maxima* and in *Crassostrea amasa* from reefs at Lizard Island, North Queensland. The widespread occurrence of *Perkinsus* spp. was confirmed in Tridacnidae and other families of bivalves from the Great Barrier Reef in an extensive survey by Goggin and Lester (1987). These authors described the occurrence of *Perkinsus* sp. in a moribund *T. gigas* at Lizard Island, but the role of the organism in the epizootic mortalities remains obscure.

In detailed pathological, bacteriological, parasitological and virological examinations of cultured populations of *T. gigas* destined for translocation from Orpheus Island in 1986 and 1987, a spectrum of protozoa, metazoa and bacteria were identified (Humphrey — unpublished data; Humphrey et al. 1987). In these examinations numerous bacterial species were isolated consistent with descriptions of the normal flora associated with other bivalves (Lauckner 1983). Bacteria of known or suspect pathogenicity for molluscs were identified also. *Vibrio alginolyticus* and *V. anguillarum* have been associated with mortalities in larval and adult oysters including *Crassostrea virginica, C. gigas, Ostrea edulis*, and clams *Mya arenaria* (Lauckner 1983; Sparks 1985). These organisms, however, are commonly isolated from healthy bivalves (Lauckner 1983).

No cytopathic viral agents were isolated from the clams.

Two metazoan agents were isolated on the first examination. These were identified by the British Museum of Natural History as the cosmopolitan free-living nematode *Syringolaimus striatocordatus* and an immature turbellarian.

TABLE 1. Partial list of diseases, parasites, pathogens and epiphytic or commensal species identified in *Tridacna* spp.

Viruses and Viral Diseases	
None Reported	
Bacteria and Bacterial Diseases	
Acinetobacter lwoffi	Humphrey et al. 1987
Enterobacter agglomerans	
Pseudomonas chlororaphis	
Pseudomonas cepacia	
Pseudomonas spp.	
Vibrio alginolyticus	
Vibrio anguillarum biovar II	
Vibrio cholera (non = 01)	
Vibrio fluvialis	
Vibrio harveyi	
Vibrio logei	
Vibrio marinus	
Vibrio natriegens	
Vibrio pelagius biovar I	
Vibrio spp.	
Larval infections	Glazebrook 1987
Metazoa and Metazoan Diseases	
Syringolaimus striatocordatus (Nematode)	Humphrey et al. 1987
Immature turbellarian	Humphrey et al. 1987
Larval bucephalid trematode	Shelley et al. 1988
Protozoa and Protozoan Diseases	
Perkinsus spp.	Perkins 1985 Goggin and Lester 1987
Unidentified ciliate	Glazebrook (pers. comm.)
Unidentified protozoan(?)	Humphrey et al. 1987
Diseases of Unknown Aetiology	
Epizootic mortalities	Alder and Braley, This Monograph

On the second examination, four of 60 clams were found to contain small ovoid to round discrete agents 1.5–5 μm in size. These agents were present in moderate to high numbers and were conspicuous in the mantle tissue. Basophilic reticuliform internal structure was evident by haematoxylin and eosin staining, but there was no evidence of vacuolar or nuclear formations. The agents could be found in most tissues of affected clams. The identity of the agents and their pathogenic significance remains unclear.

A summary of pathogens, putative pathogens and epiphytic or commensal organisms identified in *Tridacna* spp. is given in Table 1. The occurrence of these agents, or other possibly unidentified pathogens in *Tridacna* spp., demonstrates the potential to disseminate such agents when translocating populations. The responsibility in ensuring freedom from pathogenic agents or extraneous species clearly lies with the country or organisation moving the species. Such movements must be subject to stringent health certification and quarantine safeguards to prevent similar occurrences of disease and introduction of exotic agents as have occurred with other molluscan species. To translocate *Tridacna* spp. without such safeguards is clearly negligent and shows a disregard for existing fisheries and the environment in general.

Health Certification Procedures

The following should be regarded as a guideline for the effective health certification of *Tridacna* spp. prior to translocation.

Broodstock

Broodstock should be derived from areas with no history of disease and should represent healthy and well-developed specimens.

Holding Facilities and Quarantine

Ideally, larval clams destined for translocation should be reared in a recirculating, isolated facility with no direct access to the marine environment. Water should be filtered and subject to ultraviolet sterilisation. A high-capacity biological filtration system is essential. Water quality should be monitored, especially for ammonia, nitrite, nitrate and pH. Hardness should be maintained by use of shellgrit or coral sand in the system. Water changes should be undertaken using prefiltered and sterilised clean ocean water. The system must remain isolated to prevent introduction of pathogens from the sea.

Clinical Observations

The health of broodstock populations and of cultured clams should be continually monitored. All mortalities should be recorded and their cause determined. Growth rates of clams should be monitored and causes of suboptimal growth determined.

Sampling Procedures

Health certification procedures are based on detailed examinations of a representative subsample of the population under examination. Factors relating to sampling of fish for pathogens are discussed by Amos (1985) and include

- Collection of samples on a lot by lot basis, i.e. from a group of the same species and age that have a common broodstock population and common water source.
- Sampling should be biased towards poor or moribund specimens, then and thereafter on a random basis.

- Sampling is to be conducted on a basis that will detect a certain minimum prevalence of infection, usually 2 or 5%, with 95% confidence. Thus, in a population exceeding 2000 individuals, 150 individuals are required to detect a 2% prevalence, and 60 individuals to detect a 5% prevalence.
- Live or fresh sample should be examined.

It is important to note that any testing procedure presumes the techniques used will be of sufficient sensitivity and specificity to identify those pathogens or agents being sought.

Gross and Subgross Pathological Examination

External and internal shell surfaces should be examined by eye and under a stereo microscope for epiphytic organisms or for developmental anomalies. The external surface of the soft tissues is exposed by incision of the adductor muscles. The soft tissues are again examined by eye and under a dissecting microscope.

Histopathological Examination

Soft tissues of clams for histological examination are immersed in fixative. Ten percent formalin in seawater is recommended. With small individuals up to 5–6 cm multiple sections representing a spectrum of tissues and organs at different levels may be taken. For routine staining of paraffin-embedded sections, haematoxylin and eosin is used, with special stains as required.

Parasitological Examination

Metazoa detected by eye or subgross examination should be removed and fixed in an appropriate fixative. Wet preparations of gill and mantle tissue should be examined for protozoan or metazoan agents. Details of appropriate parasitological procedures are given by Gudkovs (1986). Examination of histological sections for parasitic or epiphytic agents should be undertaken. Examination of tissues for *Perkinsus* spp. may be done using thioglycollate medium to promote development of the prezoosporangia as described by Ray (1966).

Virological Examination

Virological studies of molluscs are hampered by the absence of continuous cell lines for virus isolation procedures. Virus isolation procedures using fish cell lines have been undertaken, however, as at least one virus of fish, the birnavirus of infectious pancreatic necrosis, is reported in a wide range of molluscs (Hill 1982) and others may exist. An overview of suitable techniques for virus isolation is given by Williams (1986). Virus isolations may be conducted on whole clams pooled in groups of five, macerated and inoculated onto rainbow trout gonad cells, or other cell lines.

Bacteriological Examination

Bacteriological examination of shellfish requires a specialised knowledge of the principles of isolation and identification of bacterial pathogens from fish and shellfish, together with appropriate facilities and reagents.

Clams for bacteriological examination should be air-dried, each side exposed to ultraviolet light for 15 min, then opened aseptically. Whole clams may be aseptically macerated for culture, or shell liquor and specific organs or tissues cultured. Samples should be inoculated onto marine blood agar and incubated at 20 or 28°C and colonies representing all morphological types selected and subcultured for identification. Additional information or techniques used can be found in Humphrey et al. (1987), Colwell (1983) and Bryant et al. (1986).

Conclusion

The final decision to allow the movement of a population of molluscs should rest with the examining pathologist. The occurrence of disease in the population or the demonstration of infectious pathogens must immediately preclude movement. Likewise, the demonstration of agents of unknown pathogenic significance is also sufficient justification on which to withhold movement. The occurrence of ubiquitous potential pathogens, for example, *Vibrio* spp. and the subsequent action to be taken must be a matter for discretion. Absence from disease, despite the isolation of such agents, is prima facie evidence that such organisms may not be virulent. Conversely, an association between these agents and current or preexisting disease should warrant considerable caution in allowing the translocation of the population.

Chapter 10
Socioeconomics

Socioeconomic Considerations in Giant Clam Mariculture

C. Tisdell* and K. Menz**

Abstract

On the basis of information to date, the economic aspects of giant clam farming appear to be favourable. Further data on price and production parameters are required to increase confidence in that conclusion. Property rights considerations to clams and to areas of seabed will be critical to the success or otherwise of clam farming. Regardless of the profitability of clam farming, limited hatchery stocks and the growth rate of clams imply a 10-year delay in the flow of large numbers of clams onto the market.

THE development of clam mariculture techniques has come at a time when tridacnid stocks are seriously depleted and a number of species have disappeared from their former range in the Indo-Pacific area. The IUCN has placed *Tridacna gigas* and *Tridacna derasa*, the two largest clams, on its endangered list (IUCN 1983), and most species appear now to be on the CITES list.

Clams are of particular interest to atoll countries in the Pacific which have limited resources available to them and for which marine areas are the most significant resource (Tisdell and Fairbairn 1983, 1984). According to estimates made by Heslinga et al. (1984) edible meat production per hectare per year from clams almost equals that for mussels (which are heterotrophic and intensively managed) and far exceeds that for tilapia.

The purpose of this paper is to provide a brief summary of some aspects of a consultant report by Professor C. Tisdell, assessing the socioeconomic potential of giant clam mariculture.

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Utilisation of Cultured Clams

All portions of the clam except the kidney can be utilised by humans. The adductor muscle, the mantle and shells have been internationally traded in recent times. For example, as at 1986 Solomon Islands was exporting small quantities of frozen muscle and mantle to Australia, and Fiji was exporting frozen muscle to Australia. It is believed that some of this is reexported after obtaining Australian health certification. Taiwan and Hong Kong are possible markets as well as Japan and the USA. The Philippines appear to have been an important centre for the shell trade and clam shells were until recently exported from there to many places (including Australia) to be sold in shell and souvenir shops. Most of the shell exported from the Philippines was obtained either within the country or imported from Indonesia. With natural stocks dwindling in this area, supply of shells has become scarcer. In fact, in 1987 the Philippines banned the export of shell, although some temporary relaxation was made for stocks said to have been held in Mindanao prior to the introduction of the embargo. While no exports of clam shell from Fiji (or on any scale other islands in the South Pacific) appear to have taken place, a potential may exist.

For international markets, the mature clams must be collected, prepared and packed. The muscle must be separated from the mantle and the kidney discarded. These products have to be frozen and

packed for shipment, and stored under controlled cold-room conditions until shipment or sales. The exporter needs skills in arranging international exchange. The required infrastructure is present in Fiji and to some extent in Solomon Islands since exports of frozen clam meat is taking place. In both cases a structure exists that could be expanded to cater for exports of maricultured clam meat.

Constraints to Production

Hatcheries

The rate of expansion of clam mariculture in the South Pacific is likely to be constrained by several factors. The supply of juveniles from hatcheries can be expected to be a basic constraint. Recently a pilot hatchery has been established in Solomon Islands by the International Center for Living Aquatic Resources Management (ICLARM), and in Fiji by the Department of Primary Industry. If a hatchery were to begin operation immediately, about 7–7.5 years would be required before its progeny would contribute to clam supplies, assuming that the normal length of the grow-out phase is 5 years. Hence, it is likely to be around a decade before cultured clams can add appreciably to supplies.

Property Rights

The success of farming depends upon property rights being established in grown-out clams. Many areas in the Pacific suitable for farming clams belong to traditional owners (Carrier 1981). While the government may claim all the area below high tide mark, in practice governments in many Pacific countries cannot ignore the claims of traditional owners. The right of an outside person or company to use a marine area may depend upon consent from traditional owners (village groups, tribal groups, etc.) as well as the government. In most places in Solomon Islands and Fiji the consent of traditional owners would be required and in some cases ownership may be disputed. In Fiji, a check may be made with the Native Land and Fisheries Commission as to owners according to their records but, in addition, further local checks are advisable to determine whether village groups accept the Commission's allocation (Asesela Ravuvu, pers. comm.).

It would be possible for a village group or cooperative to farm clams in its own right or to make arrangements with others to do this in a marine area belonging to the village. In the latter case the success of the venture is likely to depend on village involvement in it and the establishment of incentives to conserve the stock, that is, incentives to prevent others from raiding the stock or the villagers from taking it themselves. In places where marine areas have been alienated, the government may be able to give property rights to commercial growers as is done for oyster farmers in Australia.

Parameters for Calculating Optimal Grow-Out Period

Selected data for a cohort of 10 000 clams for 1–10 years of grow-out are presented in Table 1, based on the values and biomasses in table 3 of Munro (1985). Of these estimates, Munro says they 'are based upon what are presently considered to be the most likely values for the production parameters and wholesale prices. It is emphasised that these are not definitive values. The tabulations in this paper are computer-generated and the parameters and values can be varied as more and better information comes to hand' (Munro 1985, p. 3).

The growth rates for clams are assumed to be roughly the medians of values for *T. gigas* in Papua New Guinea and on the Great Barrier Reef (for details see Munro 1985). The mortality estimate is that for *T. derasa* reported by Heslinga and Watson (1985) for grow-out in Palau.

As for the price-values used, these are more speculative. Munro (1985) says there is little solid evidence upon which deductions could be based. His calculations assume that primary producers are paid US$10/kg for adductor muscle and US$1.50/kg for the mantle. However, these figures are undoubtedly in excess of the prices paid to primary producers in

TABLE 1. Number of clams surviving out of 10 000 (M = –.11) and value for clams 1–10 years after grow-out according to Munro's (1985) estimates.

	Years after stocking with 10 000 10–12-cm clams									
	1	2	3	4	5	6	7	8	9	10
Number of clams surviving	9003	8106	7298	6570	5916	5326	4795	4317	3887	3499
Value/clam (US$)										
Adductor only ($10.00/kg)	.27	.69	1.30	2.06	2.91	3.82	4.73	5.64	6.50	7.32
Mantle only ($1.50/kg)	.29	.73	1.38	2.18	3.08	4.04	5.01	5.59	6.88	7.74
Shell only	1.00	2.23	3.55	4.59	5.06	4.74	3.53	2.80	3.23	3.63
All meat	.55	1.42	2.68	4.23	5.99	7.85	9.74	11.60	13.39	15.06
All meat and shell	1.56	3.65	6.23	8.83	11.04	12.59	13.27	14.40	16.61	18.70

Fiji in February 1986. The discrepancy possibly arises because Munro's figures are for wholesale prices, the price received by the processor and wholesale distributor, and are not the prices received by suppliers of clams. The processor and distributor has to cover the cost of collecting and processing clams and arranging sales, and this can be considerable.

Primary producers are likely to be paid at site a price of F$1/kg or less for clam meat inclusive of both muscle and mantle. Indeed, it has been said that they would be lucky to get that much at site and more likely the payment would be around F80¢/kg (T.J.H. Adams, pers. comm.). (In February 1985 when these figures were indicated to apply, the Fiji dollar was roughly on par in value with the US dollar.) In assessing the profitability of a farming enterprise one must, of course, take account of the price paid at the farm-site, not the price received by wholesalers for the produce.

The value of shells is even less certain than meat. After considering the high prices paid for shells in the Philippines for clams, Munro (1985) estimates shell prices for the purpose of his computer-based calculations. He says shell prices have been arbitrarily set on a declining scale from US$0.75/kg for the smallest shells to US$0.10/kg for shells over 50 cm in length. It is true that the value of clam shells in the Philippines was very high, but no significant market has been found for shells in the southwest Pacific Islands.

However, this situation may change, since not all opportunities for sale of shells have yet been explored. A thorough investigation of the economic potential for shells is required.

Munro (1985) points out that value of shells in the Philippines is very high, possibly in response to a diminishing supply, and it would be unwise to place too high a value on clam shells if large-scale production systems become operational. There is a need to explore the depth of the market for shells and their end-uses.

In considering the optimal length of grow-out from a profit-maximising viewpoint three hypothetical situations are considered.

(a) the optimal length of grow-out on the basis of Munro's estimates of production and prices for meat and shell;

(b) the above on the basis that only meat is saleable at A$1.50/kg;

(c) the above on the basis that only meat is saleable at A$1/kg.

Situation (c) seems to be closest to the current situation in Fiji.

Apart from the value of yield, account needs to be taken of farming costs to assess the profitability of clam farming. Munro (1985) suggests that: 'the costs of operating a 1 ha farm appear to be modest. The principal cost would be the cost of purchasing these juveniles or of raising the necessary numbers of juveniles in an ocean nursery after having purchased the spot from a hatchery.'

Labour requirements would be one of placing juveniles in grow-out positions and possibly checking to remove predators and harvesting as required for market. These would be periodic activities that could be interspersed with other activities and engaged in in times of low demand for labour. If clams are grown within a clan or village structure, labour costs might be negligible. Labour costs will depend on the institutional arrangements for farming clams.

As Munro points out, 'the principal unknown cost at present is the purchase price of juveniles. This will be dictated by the operations of the hatchery and nursery phases.' Calculations suggest a cost per 2-year-old juvenile clam of A80¢ to A$1.25 with a price of around A$1 per juvenile very likely. It is interesting to consider whether farming could be economic at these prices.

Optimal Grow-Out and Maximum Price

In this section, the length of the period for grow-out which maximises the present discounted value of a batch of juvenile clams is considered. This enables us to determine the length of time required to maximise gains from growing-out clams if the only cost of major consequence is the cost of juveniles. The maximum net present value of a juvenile clam grown-out represents the maximum price which a farmer could pay for juveniles and obtain the rate of return implied by the interest rate used for discounting. If the actual price is less than this price, the farmer obtains a higher rate of return.

Estimates of the expected net present value of growing out juvenile clams of about 2 years of age were calculated. The value is obtained by multiplying the estimated market value of a clam by the probability of survival of a juvenile clam and discounting this sum using the appropriate rate of interest. Where P_t represents the probability of a juvenile clam surviving to the end of year t of grow-out, where M_t is the estimated market value of the clam at time t and r is the discount rate, the present discounted value (PDV) of a juvenile clam after t years of grow-out is

$$PDV = (P_t M_t)\, e^{-rt}$$

percent. The higher the rate of interest, the lower the present value of a juvenile. If no discount is applied it is $6.67. At 5% rate of interest it is $5.07 and at 10 and 15% $3.95 and $3.20, respectively. If a farmer paid $3.20/juvenile under these conditions, he could expect to obtain a 15% return. At a price of $1.85/juvenile, he could expect a 30% return. Under Munro's (1985) assumed conditions (Table

TABLE 2. Maximum expected present discounted value of grown-out 10–12-cm juvenile clams and years to this maximum for meat only at $1.50/kg.

Discount rate	Maximum expected PDV, $	Years of grow-out to maximum expected PDV
0 (undiscounted)	3.09	10
0.05	1.97	8
0.1	1.37	7
0.15	.99	6
0.2	.77	5
0.25	.60	4
0.3	.50	4

TABLE 3. Maximum expected present discounted value of grown-out 10–12-cm juvenile clams and years to this maximum for meat only at $1/kg.

Discount rate	Maximum expected PDV, $	Years of grow-out to maximum expected PDV
0 (undiscounted)	2.06	10
0.05	1.31	8
0.1	.91	7
0.15	.66	6
0.2	.51	5
0.25	.40	4
0.3	.33	4

1), clam farming would be *very profitable* since juveniles could be expected to cost much less than $1.85 each.

In the absence of any discounting, the optimal length of time for clam grow-out is 6 years, but with the discount rates of either 0.05 or 0.1 it is 5 years dropping to 4 years for discount rates of 0.15 and 0.2. The higher the discount rate the shorter is the time that it pays to hold grown-out clams. This would suggest in practice that a 4–5-year grow-out period is likely to be optimal.

The market values, however, assumed by Munro seem overoptimistic. Expected present value of juveniles based on less optimistic assumptions are set out in Tables 2 and 3, respectively, together with the length of the period of grow-out required to maximise expected present discounted values.

At an interest rate of 10%, the maximum expected present discounted value of a juvenile clam is $1.37 if clam meat sells for $1.50/kg and 91¢ if clam meat sells for $1/kg and this is the only saleable product from the clam. Farmers could afford to pay these prices for juveniles and would receive a real return of 10% on the outlay given the assumptions made. On the basis of previous calculations, these prices for juveniles appear to be achievable. Note that the optimal length of the grow-out period is 7 years in these cases rather than 5 years as in Munro's (1985) case, but it drops to 5 years if a 0.2 discount rate is applied.

At the present time, a 10% real interest rate may be appropriate (but, of course, due to inflation the actual interest rate may be higher). If a 10% interest rate is adopted, clam farming would appear to be very profitable under Munro's assumptions, quite profitable if clam meat only can be sold at $1.50/kg and marginally profitable to slightly unprofitable if clam meat only can be sold at $1/kg assuming that juvenile clams can be supplied to farms at prices in the 90¢ to $1 range. At the time of the original report (1986) the last scenario seemed the most likely as far as Fiji is concerned. However, the price of juveniles may be brought down lower than are the assumed values. Certainly, these results are not grounds for economic pessimism about clam mariculture projects. Indeed, on the contrary, since clam mariculture is still in the early stages of development these results provide some grounds for optimism.

Future Studies

Production Economics

Revise and refine production economics models in light of new information on clam raising technology and with better information on costs and resources.

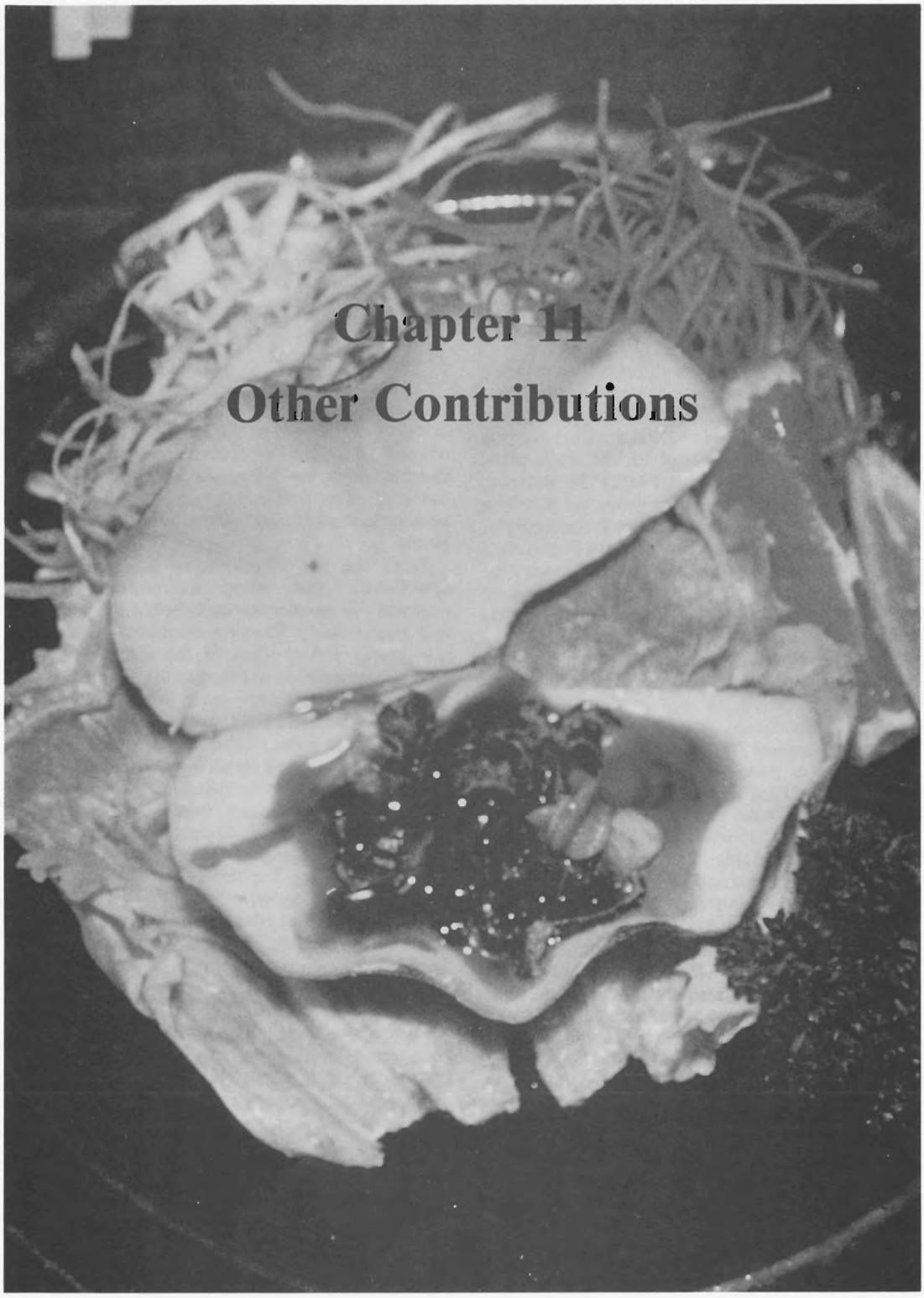
Marketing Studies

To the extent possible using economic analysis, consider the market prospects for giant clam products. This will involve obtaining better price information, and attempting to define the depth of the market (for all clam products). It is not only important to obtain good information on *current* prices for clam products, but to attempt to assess whether these prices would 'hold up' in light of supply increases. A quantitative assessment of this issue based upon historical price and quantity movements is not likely to be feasible, given the data limitations.

However, a descriptive analysis of the current and historical market situation may allow a reasonably confident assessment to be made of this issue.

Country Studies

To delineate which countries are most likely candidates for commercial clam mariculture, on the basis of physical environment, socioeconomic conditions and marketing/transportation considerations. A limited range of countries only can be assessed — perhaps Australia, Philippines and Kiribati for example, as examples of an industrial, less developed and atoll country, respectively.



Chapter 11
Other Contributions

Cooperative Program on Giant Clam Culture with Philippine Fishing Communities

A.C. Alcala*

Two laboratories in the Philippines have been conducting research on the culture of giant clams. These are the Silliman University Marine Laboratory (SUML) in Dumaguete, Negros Oriental, and the University of the Philippines Marine Science Institute (UPMSI) in Bolinao, Pangasinan. These research programs are part of a larger program including James Cook University in Townsville, Australia, the University of Papua New Guinea, and the Fisheries Division, Ministry of Primary Industries in Suva, Fiji. It is supported by the Australian Centre for International Agricultural Research (ACIAR) (Lucas 1986).

The target species in the breeding program are the two largest and fastest-growing species, *Tridacna gigas* and *T. derasa*, as well as the China clam *Hippopus porcellanus*, which is highly desired for its shell. However, because of a shortage of broodstock for these species, partly as a result of overcollecting (Alcala 1986; Juinio et al. 1988), the breeding aspect of the program has focused mostly on the smaller species for which adequate broodstock is available. These species include *T. squamosa, T. maxima* and *H. hippopus*. Only a few spawning events involving *T. derasa* and *H. porcellanus* occurred at SUML.

The primary objective of the Giant Clam Project is to breed clams for food and for restocking denuded reefs. Thus clam culture could serve as an incentive for coastal communities to conserve coral reef resources. To fulfill this objective, the two Philippine laboratories have been promoting the culture of giant clams in the central Philippines (SUML) and northwestern Luzon (UPMSI). This paper describes the cooperative program with fishermen and the progress achieved during the past 3 years.

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Community Involvement

The program takes various forms, differing in the extent of community participation. Common to all of them are discussion sessions on clam culture and dispersal of a few thousand juveniles for ocean nursery. The three forms of cooperative involvement of fishing communities are described below.

First, the use of protected areas (reserves) established and administered by fishing communities as sites of broodstock development and ocean nursery. The project researchers monitor the growth and survival of the clams, with the community assisting in maintaining the clam cages and in keeping watch over the animals. The community benefits in some ways: a small honorarium is given to the fisherman assigned to watch the clams; the clams serve as attraction to tourists who pay fees for using the reserve; and all animals added through natural reproduction become part of the community's resources. Examples of reserves used for broodstock collection and ocean-rearing are those in Apo island (off southeastern Negros), Balicasag Island (off southwestern Bohol Island), Pamilacan Island (off southeastern Bohol), and Silaqui Island (north of Santiago Island, near Bolinao, Pangasinan). (A portion of Silaqui Island is being protected prior to becoming a reserve.)

Second, the use of suitable reef areas leased to commercial *Eucheuma* (algal) farmers for clam rearing. In effect, clams are polycultured with the algae. The project personnel monitor growth and survival of the clams, and the algal farmers provide protection. The expectation is that algal farmers would eventually take up clam culture as a supplementary, income-producing activity. This arrangement is exemplified by the cooperative effort between SUML and Marine Colloids Philippines, Inc. operating in the Danajon Reef, off northern Bohol.

Third, the popularisation of giant clam culture among fishing communities organised by the Central Visayas Regional Project (CVRP), a development project for the Central Visayas, comprising the provinces of Bohol, Cebu, Negros Oriental and Siquijor (Anon. 1986). The nearshore fisheries component of CVRP promotes the management of shallow-water marine resources through such schemes as protection of marine environments, rehabilitation of degraded habitats, and ranching/farming of economically important species. Implementation of these activities is through fishermen's organisations. The Giant Clam Project has worked with these organised communities in the provinces of Negros Oriental, Cebu and Siquijor. Some community groups and individual members of the community have reared juvenile clams in ocean nurseries for experimental purposes. The SUML gave them juveniles free of charge, provided they signed an agreement to leave 50% of the surviving individuals to repopulate the reef. The Negros Oriental CVRP group has just ordered 6000 clams for ocean-rearing in 1988.

The promotion of giant clam culture is not limited to community groups. The project has encouraged individual fishermen who are not members of fishing organisations to become cooperators in clam farming/ranching. Clam juveniles are sold to them at low prices. One enterprising cooperator (a shell dealer) in Bantayan, Dumaguete City, has already begun selling his cultured *H. hippopus* to tourists after a year of growing out his animals.

Concluding Remarks

It is important that the UPMSI and SUML demonstrate that giant clams can be successfully grown in reef areas. The culture of these species, together with the ranching/farming of other economically important marine species, could be an important component of a strategy to increase the productivity of shallow marine areas in the Philippines. The other components, as practiced by the CVRP in the Central Visayas, include environmental protection and rehabilitation. However, before clam farming/ranching can succeed, some problems need to be addressed and solved. These are the availability of broodstock of the target species, the institution of tenurial policies designed to encourage the culture of clams, the creation of ready markets for giant clam products, and the production of a simple primer on clam culture.

Giant Clam Exploitation in the Southwest Pacific

R.F. Dawson*

CHINESE fascination with this fabulous sea-creature goes back to ancient times when it was prized more for the shell's lapidary uses. 'Neptune's Cradle' was the name given to the shell (Schafer 1963). Today, the giant clam is prized more for the adductor muscle, which is considered a delicacy, particularly among Taiwanese.

Changing Attitudes

The clear message which emerged from recent discussion with some foreign clam boat owners was that they would not be returning to Pacific waters. The perceived high risk of detection and apprehension appears to have been an effective deterrent. It would seem that a hardening of attitude by Asian authorities toward clam boat operators whose vessels were involved in prosecutions, has also had some impact. In earlier years, the national authorities have been far more lenient on owners whose vessels had been forfeited as a result of prosecutions in other countries.

Aerial surveillance, a surface enforcement capability and a 320-km declared fishing zone (AFZ) have proved to be a successful combination in combating the poaching problem in Australia. The problem still exists, however, for the small countries throughout the southwest Pacific which lack the necessary surveillance and enforcement elements. The only effective weapon which some countries have had at their disposal as a deterrent has been harsh penalties. To give an example, in Palau, one clam boat captain who had been apprehended twice within a year (1984) received a maximum 3-year gaol term and fine of US$50 000.

In 1986, sources involved in the clam fishing industry assessed that clamming would continue for only another 2 or 3 years. People were leaving the industry, primarily because of the increasingly poor earnings. Based on this and other factors, such as the perceived growing risk of losses through apprehension and greater opportunities in more stable occupations in countries of growing affluence, one might predict that the Asian clam boat era is drawing to a close.

Mariculture and the Market

There is some evidence that Taiwanese are engaged in giant clam mariculture. If, indeed, this is the case, and if they successfully develop a clam farming industry, it could have a significant effect on the prospects of other countries looking to supply international markets, particularly Chinese markets.

It is believed that a giant clam mariculture facility has been established in the South China Sea.

It is also noteworthy that an expression of interest in a giant clam joint venture agreement with an Australian company has come from the People's Republic of China (PRC). No further details are available, other than the fact that technical expertise for such a project would be supplied by the Chinese. Interest has also been shown by the PRC in the Micronesian Mariculture Demonstration Center in Palau, as evidenced by a visit of a Chinese person, persumably a marine biologist, to the Koror facility, recorded in the Center's second quarterly report for 1985.

The results of a survey of the market for giant clam products in Asia, which was carried out for the FFA in January/February 1986, revealed that the only existing market was in Taiwan and the product was frozen adductor muscle. The market was confined to the exclusive restaurant trade and the maximum volume was assessed by Taiwanese experts as being approximately 100 t.

In 1985 only about 50–60% of market demand was being met. The previous year, supply was assessed at around 60–70%; a continuing downward trend in market supply was expected through 1986 and onward.

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The best price for clam muscle, according to suppliers, was to be obtained on the Taiwanese market. If a situation were reached whereby supply exceeded exclusive restaurant trade demands, muscle would be exported to Hong Kong for the exclusive restaurant trade there. Expanding the market within Taiwan to include lesser quality restaurants and other retail outlets, such as supermarkets, would result in a lower price for the product, and was not considered as an option (Dawson 1986).

During the course of the market survey, Hong Kong and Singaporean suppliers of marine products who were interviewed all targeted the exclusive restaurant trade as the potential market. In the main, they were referring to Chinese restaurants. One of the Singaporean contacts included quality Chinese restaurants of Malaysia and Thailand when calculating the volume of the potential market which he might supply. The situation would be similar in other countries with concentrations of ethnic Chinese and sizeable Chinese commercial centres. Around the world, Chinese commercial links are well established and there is a very efficient network of contacts and information exchange. Market penetration would be extremely difficult for outsiders if Chinese producers were able to supply a Chinese market.

The survey also found that the exclusive sushi restaurant trade in Japan might offer considerable market potential. There were doubts, however, as to whether Japanese consumer conservatism might be an obstacle to acceptance of a new product. If a market were to open up in Japan, Taiwanese suppliers who have long-established ties in providing marine products for Japanese markets might have a decided advantage over other suppliers.

With the undersupply situation of the lucrative Taiwanese clam market becoming more acute, Taiwanese and other Chinese will continue to explore avenues to harvest wild stocks. The more remote island countries are more likely to be their targets.

Both Taiwan and the PRC appear to have the technical expertise for giant clam mariculture. It is possible that the PRC might be engaged in clam mariculture work around Hainan Island. A likely development would be that Taiwanese and PRC interests will seek joint venture arrangements in other countries.

Joint ventures with Taiwanese or PRC participation and partnerships with local overseas Chinese would provide greater assurance of access to Chinese markets. Taiwanese participation might also enhance prospects for entry into a Japanese market.

Use of Giant Clams in Japanese Cuisine

Lynda Cowan*

A TOTAL of twenty 2- and 3-year-old clams from the Orpheus Island Research Station were delivered to a restaurant in Parramatta on the evening of 26 October 1987, approximately 12 hours after they had been taken out of the water and airfreighted. Only three specimens were obviously stressed, showing no reaction to touch stimulus on the mantle. These animals were set aside for cooking as they therefore could not be used for raw dishes.

This mortality rate is satisfactory considering total time out of water and that no special methods were used apart from packing in wet newspaper. Air temperatures at the time of packing were about 25°C and temperature of the aquarium water was about 27°C.

For the purposes of export and interstate marketing when longer journeys will be necessary, it may be advantageous to gradually cool the clams before packing to temperatures near the lower limit of their range (perhaps 20°C) in order to reduce metabolic rate. As a packing medium, wet newspaper is not ideal as it is very heavy and greatly increases freightage. Lightweight material such as several layers of wet Chux Superwipes to retain humidity, and individual plastic bubble wrap for protection, should suffice.

Preparation of the Clams

The Japanese chef, after the first few attempts, was able to rapidly shuck the clam meat and separate the mantle and adductor muscle from the viscera in just a few seconds. However he did feel that handling the 2-year-old clams was a lot of bother considering the relatively small meat yield in comparison to the 3-year-olds.

After all the meat was separated from the clams, it was used in seven Japanese dishes, including two considered to be non-traditional or westernised, as described below. They were eaten and comments of the taste panel noted.

Most of the dishes were raw (sashimi) or only lightly marinated. It was claimed that the mantle meat had a definite 'seaweed' or 'kelp' smell and the marinades were used to just take the edge off this flavour, without masking it altogether.

The chef, a sushi expert, felt that the meat of the 2-year-olds was too thin, soft and watery for sushi (that is, a slice of raw meat on top of a vinegared rice ball), but that 3-year-old and possibly older clams might provide thicker and firmer meat more suitable for this type of dish.

Image

Because of the necessary preparation (removal of kidney, etc) before the clam meat can be eaten, it was felt that 2-year-old clams, despite the size similarity, did not fit the same market image and niche as oysters and mussels, which can be eaten as is. In this regard, it is possible to think of giant clams as similar to abalone, which of course are a much higher value product than oysters.

The shell was considered to be a marketing plus and that restaurants should be supplied with live, or at least fresh chilled, in-shell clams. The shells would undoubtedly be used to serve the clam meat. Possibly shucked chilled meat could eventually be marketed separately along with shells, which would have the advantage of being a value-added product. Shells should be cleaned of algae before sale.

Opinion was divided over whether giant clams should keep their proper Japanese name of 'Ojakko-gai,' so that the uniqueness of the product would be obvious, or to devise a more lyrical marketing name such as 'sango-gai' (coral clam).

Follow-Up

Further market research trials are required in Australia and in Tokyo. Potential customers in

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Australia would obviously include gourmet Chinese and Japanese restaurants in southern capitals as well as tourist resorts and hotels in Queensland, where the giant clam could make a very appropriate bicentennial debut.

Acknowledgment

We were greatly assisted by the staff of Inaka Japanese Restaurant, Parramatta, NSW, Australia.

The Dishes

Dish #1: 'Kaibashira Sashimi'

This is raw adductor muscle of several clams placed back in one shell, surrounded by garnishes of seaweed, carrot, radish, ginger, parsley and lemon, and topped with a sprinkle of seaweed. Accompanied by a horseradish-soy sauce dip. Rated highly by all.

Dish #2: 'Jakkogai no sashimi'

This is raw mantle meat of two or three clams placed back in one shell, with similar garnishes and dip to Dish #1. Rated as reasonable.

Dish #3: 'Sumiso'

Raw mantle meat with garnishes and traditional vinegar and miso (fermented soy bean paste)-based sauce. The strong sauce, although liked by everyone, was felt to overpower rather than enhance the flavour of the meat.

Dish #4: 'Sunomono'

Raw mantle meat marinated for 30 min or so in soy sauce, vinegar and lime juice, and served in a bowl with a marine salad. Rated very highly, equal favourite with #5.

Dish #5: 'Wafu Salad'

A Japanised salad containing orange pieces, cucumber, carrot, etc., and mantle meat which was dipped for a few seconds in boiling water. The dressing consisted mainly of soy sauce, vinegar and oil. Rated very highly, equal favourite with #4.

Dish #6: 'Tempura'

Mantle and adductor muscle meat mixed with chopped leek and covered with light tempura batter before deep frying. This dish did not work very well, possibly because of the high water content and the small pieces of meat, both of which tended to give too loose a consistency to the final mix. The taste was passable.

Dish #7: 'Butter yaki'

Mantle meat sautéed in butter, soy sauce, sake and pepper and served in shell. Taste was reasonable but not identifiably clam.

A Note on the Stocks of Giant Clams in Pari Islands and Helen Reef, Indonesia

Kasijan Romimohtarto and Sutomo*

DETAILED observations on the tridacnid stocks in Indonesia have not yet been carried out. However, investigations show the populations of these animals in several parts of Indonesia to be critically low. Wells et al. (1983) and Usher (1984) reported that the largest species, *Tridacna gigas* and *T. derasa*, are now probably extinct throughout much of the western part of Indonesia. Panggabean (1985) noted that *T. gigas* and *T. derasa* were no longer found in the Pari Islands area. For comparison, giant clam standing stocks on Helen Reef and on Pari Islands are presented in Table 1. Based on the sexual maturity data obtained by Stephenson (1934), *H. hippopus* attained maturity at 24 cm, and for *T. maxima* and *T. squamosa* at about 15–20 cm (LaBarbera 1975). It is assumed that most of the population on Pari Islands was immature. A brief investigation of the clam population carried out on Seribu Islands and Karimun Jawa Islands showed that *T. gigas* and *T. derasa* were extinct. The other species, *T. crocea, T. squamosa* and *H. hippopus*, were still found but their populations were declining. They were almost all small and widely scattered. The larger clams were found only in deeper water and were few in number.

Efforts to protect these clams were intitiated by implementing the existing regulations and laws. But because giant clams are mostly found in remote coral islands, control is difficult to maintain. Therefore, other means of protecting the clams from extinction have to be sought, and restocking using culture techniques is desirable.

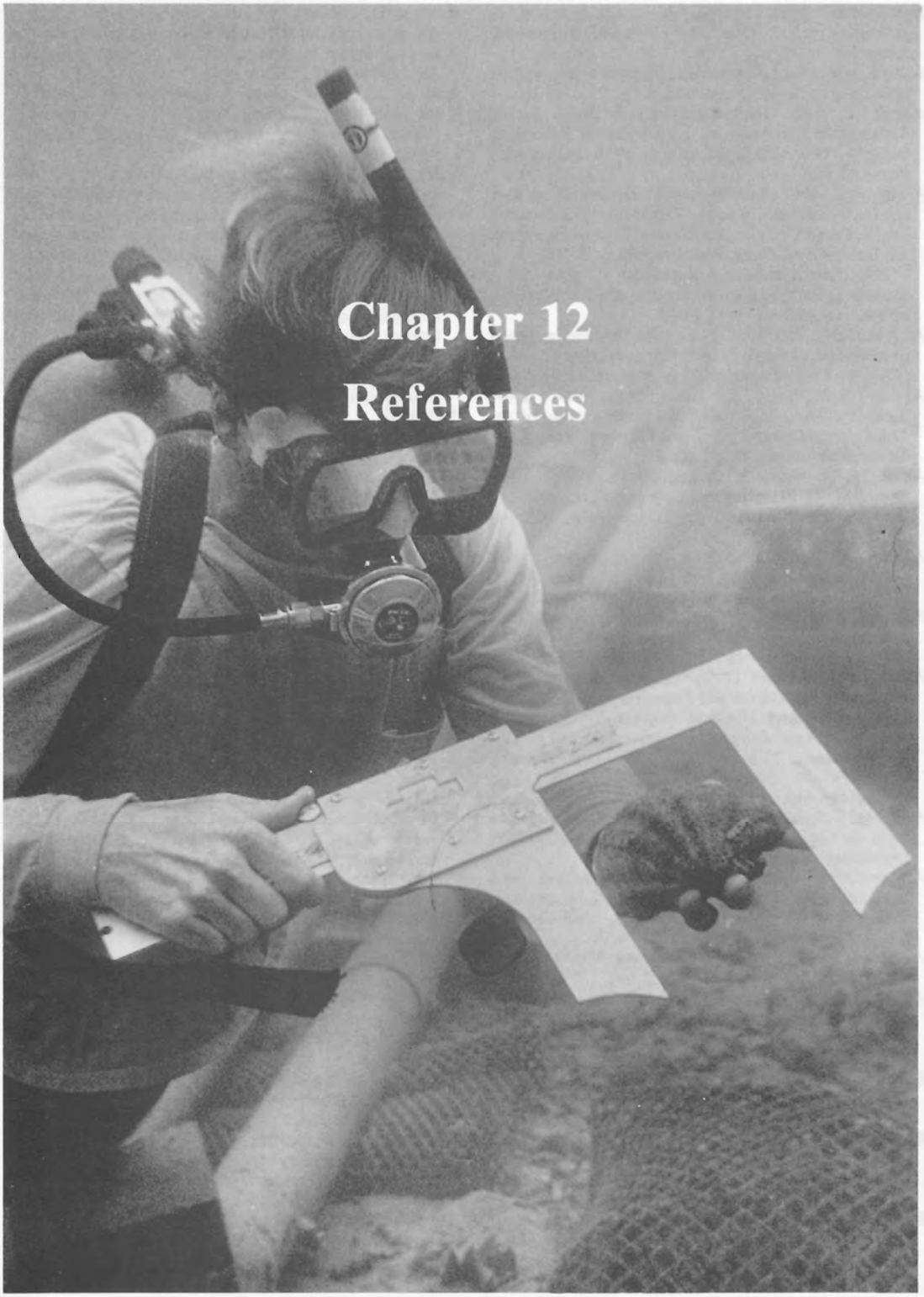
A giant clams research program in Indonesia was started by the Centre for Oceanological Research and Development (LIPI) in 1984, but because of limited funds the program did not run smoothly. Outside funding for the program is being sought. This institute has become a member of the International Giant Clam Mariculture Project.

TABLE 1. Standing stock estimates ('000s) for tridacnid species found on Helen Reef and Pari Islands.

	Helen Reef[a]		Pari Islands[b]	
Species	1972 (Hester and Jones 1974)	1975 (Bryan and McConnel 1976)	1976 (Hirschberger 1980)	1984 (Panggabean 1985)
Tridacna gigas	49.8	8.6	13.8	-
T. derasa	32.8	12.9	24.2	-
T. crocea	2.7	ubiquitous	ubiquitous	21.5
Hippopus hippopus	44.6	47.4	47.4	6.1
T. squamosa	1.2	4.3	10.4	1.2
T. maxima	1.7	1.4	1.1	1.2

[a] Area of suitable habitat 5340 ha.
[b] Area of suitable habitat 515 ha.

* Centre for Oceanological Research and Development, P.O. Box 580 DAK, Jakarta 11001, Indonesia.



Chapter 12
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