1. Introduction

There have been numerous giant-clam mariculture projects over the years. These projects have been funded by the Australian Centre for International Agricultural Research (ACIAR) and other donors, and many have had the ongoing involvement of the International Center for Living Aquatic Resources Management (ICLARM). Initially, these projects were scientific and technical in nature, but over time have become development oriented. ICLARM has made a significant contribution to the development effort through an extensive program of village-farming trials in Solomon Islands. As a result of these trials, giant-clam mariculture is emerging as a commercial export industry in that country. In this chapter, background information to the development of commercial giant-clam mariculture is provided, and the status of the emerging industry is outlined. The need for economic evaluation of research and development activities is highlighted.

1.1 Background to the development of commercial giant-clam farming

Giant clams (family *Tridacnidae*) are bivalve molluscs that occur naturally only in the tropical and subtropical marine waters of the Indo-Pacific. There are nine extant species, of which the largest is *Tridacna gigas* and the smallest is *T. crocea*. Classification keys to the most common species can be found in Rosewater (1965, 1982) and Lucas (1988). Giant clams have two main parts, the shell and the soft flesh; the soft flesh is covered by the coloured mantle. Characteristics of the shell and mantle differentiate the species. For example, *T. gigas* may grow to over one meter in shell length and has a predominantly brown mantle, while *T. crocea* grows to only about 15 cm and has a mantle with bright colours, including green, blue, purple and orange.

Natural stocks of giant clams have been seriously depleted due to traditional harvesting by expanding coastal village populations for subsistence purposes such as food, ornaments and utensils, and overexploitation by foreign fishermen for lucrative Asian markets for the adductor muscle (Copland and Lucas, 1988; Munro, 1989; Lucas, 1994). By the early 1980s, many species of clam were considered to be endangered by the International Union for the Conservation of Nature and, in 1983, all species were listed under Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Wells *et al.*, 1983; Tisdell and Menz, 1992; Tisdell *et al.*, 1994b). This listing by CITES regulates international trade for giant clams and remains in force today. It prohibits international trade between CITES signatories in giant-clam products obtained from natural stocks, but allows for export in cultured giant-clam products provided they are appropriately certified (Bell *et al.*, 1997a).

Techniques for the culture of giant clams were developed during the 1970s and 1980s. The Micronesian Mariculture Demonstration Center in Palau and the University of Papua New Guinea initially played key roles. However, it was not until ACIAR funded a major multinational research project in the mid-1980s, involving institutions from throughout the Pacific Island region (including ICLARM), that such techniques became well-established (Copland and Lucas, 1988; Tisdell and Menz, 1992; Fitt, 1993a; Tisdell *et al.*, 1994b). A variety of techniques were developed, and are documented comprehensively in culture manuals (see Heslinga *et al.*, 1990; Braley, 1992; and Calumpong, 1992). The longest established technique involves the culture of giant-clam "seed" for up to one year in land-based facilities, followed by transfer to the ocean for grow-out (Tisdell and Menz, 1992). Four main phases may be distinguished: hatchery phase, land-based nursery phase, ocean-nursery phase and ocean-grow-out phase.

The motivation for ACIAR-funded research was purportedly to develop culture techniques to restock reefs where giant clams had become extinct, and thereby provide coastal communities with stocks sufficient to satisfy their subsistence needs (Tisdell *et al.*, 1994b). However, this objective was never seriously pursued (Munro, 1997, pers. comm.). Coastal villagers were more interested in the prospects for commercial mariculture to satisfy their increasing dependence on the cash economy. Culture techniques were therefore developed with a view to commercial production by village farmers in developing countries of the Pacific Island region. Similar developments in terms of breeding, nursing and culture techniques also took place elsewhere in Southeast Asia. In the Philippines, for example, many reseeding and restocking programs were initiated by non-government organisations (NGOs) and private donors to enhance depleted natural stocks and to support conservation and livelihood programs for village communities. Experience gained there shows that although NGO and private donor support contributed to the initial mobilisation of restocking programs, poaching and indiscriminate harvesting could not be controlled in post-project situations. Investments made by NGOs and private donors could not be protected as village communities had little motivation and interest to be part of the management of restocking programs. Restocking reefs with hatchery-raised clam seed for biodiversity conservation, and to meet the subsistence requirements of village communities, has both institutional and economic implications. Community participation and cost recovery are regarded as critical elements. To date no viable institutional arrangements and financing scheme have emerged to guarantee sustainable restocking and enhancement. This could be overcome now that a commercial industry is developing; for example, village farmers could be regulated to set aside a small proportion of their cultured clams for restocking (Bell, 1999a).

In the late 1980s, ACIAR also funded research to explore the marketing opportunities for cultured giant-clam products and to assess the economics of their commercial production. Marketing opportunities have been described by many authors including Dawson (1986), Dawson and Philipson (1989), Heslinga *et al.* (1990), Shang *et al.* (1991), Braley (1992), Calumpong (1992), Tisdell (1992) and Tisdell *et al.* (1994a). The three main markets identified so far are for aquarium specimens, seafood and shells. The only active market to date is in the aquarium trade (Gervis *et al.*, 1995). However, this market is limited in size and unlikely to be large enough to support commercial culture in a variety of developing countries. Thus large-scale adoption will depend on development of the seafood market (Bell *et al.*, 1997a). The production of shells for the shell market will necessarily be linked to the production of seafood clams. Six of the giant clam species have economic potential. The preferred species for the aquarium market is *T. crocea*. The species that appears to have the best potential for the seafood market is *T. derasa* (Bell *et al.*, 1997a; Hart *et al.*, 1999). The markets appear to be located in Europe, USA, and Japan. The actual size of these markets and their potential for expansion has not been studied. Their outlook for viability and reliability hinges on both economic and institutional factors. Some experts suggest that one of the constraints to expansion of the industry is the limitation imposed by CITES. Overcoming CITES regulations is too cumbersome for small-scale farmers in many countries.

From the late 1980s to early 1990s, ACIAR also funded research into the social and institutional factors affecting the adoption of giant-clam mariculture at the village level. Coastal villagers live traditional lifestyles, reliant on land and marine resources to satisfy their subsistence needs and occasionally earn modest cash income. They do not normally participate in the formal labour market. Villagers engage in activities such as gardening, food and firewood collection, fishing and copra production, and have commitments to their community and church. Adoption of giant-clam farming will depend on factors such as the amount and cost of production inputs (including the opportunity cost of labour which depends on the value of alternative village activities), income received, transport, property rights and sharing arrangements between potential giant-clam farmers and other villagers. Tisdell (1992) and Hviding (1993) discuss many of these issues.

1.2 Status of the Industry

Although giant-clam mariculture is emerging as a commercial industry, it is still in the early stages of market development and research continues into culture techniques. ICLARM is active in both these areas. ICLARM has conducted a giant-clam mariculture project in Solomon Islands since 1987 aimed at developing viable small-scale commercial aquaculture of giant clams and the restocking of the larger species. This project is funded from ICLARM's core budget and supplemented by grants received from international donors including ACIAR, the European Union, the Economic and Social Commission for Asia-Pacific and the Food and Agriculture Organisation, as an activity within its Coastal Aquaculture and Stock Enhancement Program. The focus of this project has been a set of village-farming trials where selected villagers rear giant clams in ocean nurseries for commercial sale and experiments. The trials are designed to identify the optimal environmental conditions and farming techniques for village farming, and are based on the production of giant clams to test and develop new and existing markets. Results of the trials are the subject of ongoing publications, eg. Govan (1993), Hambrey and Gervis (1993), Bell (1999a, 1999b), Bell *et al.* (1997b), Foyle *et al.* (1997) and Hart *et al.* (1998, 1999).

ICLARM currently distributes seed clams to some 30 village farmers. The farming systems are simple, low-cost and low-input operations. They involve rearing giant clams in enclosures or sea cages until they are large enough to be virtually free from predation and able to withstand environmental stresses, when they are then placed directly on the sea floor. The main inputs to production are clam seed, labour and time. No feeding is required, as the clams obtain their nutrition from photosynthesis and by filter-feeding particulate organic matter contained in the seawater (Klumpp *et al.*, 1992; Klumpp and Griffiths, 1994). Labour input is used for planting, cleaning, thinning, and harvesting of clams. Planting involves placing the seed clams into cages so that they attach firmly to the concrete base. Cleaning is an important activity; it involves keeping the cages free of predators and algal build-up. Thinning involves reducing the number of clams per cage (increasing the number of cages) as they grow; it is undertaken to avoid the negative effects of crowding. Harvesting involves collecting clams of marketable size from the cages and preparing them for transport and sale.

ICLARM produces the seed clams for the farming trials and sells them to the village farmers for grow-out. ICLARM undertakes regular farm visits to monitor the growth and survival of the seed and to encourage farmers to embrace good farming practices; it also coordinates the buy-back of clams from farmers once they reach marketable size for sale to local exporters. ICLARM is therefore in a monopoly/monopsony position – it is the only supplier of seed clams and the only buyer of marketable clams in Solomon Islands, and it only undertakes these activities with village farmers involved in its project. ICLARM's approach to the project is described by Gervis *et al.* (1995) and Bell *et al.* (1997c). ICLARM proposes to transfer these responsibilities to a private giant-clam hatchery operation once all aspects of the operations have been demonstrated to be viable.

Besides assisting the village farmers with seed clams and the farming technology, ICLARM's development effort has led to exploring international markets for the various types of cultured giant-clam products (eg. Riepen, 1998). ICLARM has also played an enabling role by obtaining the relevant CITES certificates and permits for the products to be exported. This has launched village farmers into commercial production by securing a market for their produce. ICLARM has assumed this role to demonstrate the full potential of the farming technology. Once links with the market are established and institutional issues (eg. CITES regulation) become easier to handle, it will become a private sector activity. Alternative institutional arrangements for such functions in small developing country economies are clearly lacking at present.

1.3 The need for evaluation

ICLARM believes that funding should continue for giant-clam mariculture until a thorough assessment of the economic viability of the emerging industry is complete or until the industry is fully commercialised (Bell and Gervis, 1999). As a precursor to future funding, however, there is significant need for a comprehensive economic evaluation of research and development activities to help with research planning and evaluation, and for policy analysis.

Economic evaluations of giant-clam mariculture research and development have already been undertaken by Tisdell (1991) and Kearney and Hundloe (1998). Tisdell (1991) assessed ACIAR funding of the culture of giant clams for food and restocking tropical reefs. This was necessarily an *ex ante* assessment of the research benefits attributable to this funding. It was completed very early in the research and development phase and based on assumptions that have not been realised. Tisdell (1991) used a holistic framework for this assessment, including cost-benefit analysis, Conway's agroecosystem approach and evolutionary-type appraisal. Given data limitations, these analytical techniques are not particularly useful for research planning or allocating research funding.

Kearney and Hundloe (1998) reviewed ACIAR funding of large-scale village-farming trials recently undertaken by ICLARM, as part of an *ex post* and *ex ante* evaluation of ACIAR/ICLARM research into the mariculture of several commercially important coral-reef invertebrates, including giant clams, blacklip pearl oysters and beche-de-mer. Kearney and Hundloe (1998) did not attempt to quantify the benefits of this research for giant clams or for any other species under review. Rather, their approach was qualitative. They supported a cost-benefit approach to research benefit evaluation, but argued against undertaking such an analysis, most particularly because none of the research projects under review have progressed to the commercial stage, and sufficient data are not yet available. Nevertheless, Kearney and Hundloe (1998) identified areas for additional research and development support, although they did not justify their recommendations with any rigorous analysis.

A key point in both these studies is the lack of data for a proper economic evaluation. The research outlined in this thesis aims to considerably relax this information constraint by developing a conceptual model of the evaluation problem and integrating information available so far into a formal mathematical model using bioeconomic techniques. Bioeconomic modelling is an effective and efficient way in which to design production systems and evaluate and plan research programs, particularly when the systems are in the early stages of technical and/or commercial development (Allen *et al.*, 1984; Cacho, 1997). The conceptual model has been designed to help better understand the underlying impact assessment process, and can be used to identify knowledge gaps and guide data collection efforts. It can be used for integrated research and policy evaluation of the emerging industry, using the development of village-based commercial giant-clam farming in Solomon Islands as a case study.

ICLARM perceived the need for this research, and collaborated with the author of this thesis, to develop the model. The research was partially funded from ICLARM's core budget as an activity within its Policy Research and Impact Assessment Program. As a member of the Consultative Group on International Agricultural Research (CGIAR), ICLARM is very concerned about the outcomes and cumulative benefits of its research endeavour. Giant-clam research is important for ICLARM from the viewpoint of marine biodiversity conservation as well as for income, employment and food security for coastal communities. Systematic evaluation of the results and outcomes of the research is of priority concern (Ahmed *et al.*, 1999).

1.4 Aims and objectives of the research

The first aim of this research is to develop a mathematical model for the potential supply of giant clams from a village farm using bioeconomic techniques. The second aim of the research is to demonstrate how bioeconomic modelling can contribute to economic analysis and research evaluation of emerging industries, using the development of giant-clam farming in Solomon Islands as a case study. A conceptual model for the emerging industry is developed, which has, at its core, the bioeconomic model for potential supply. The bioeconomic model is applied to explore optimal farm management, potential supply under optimal management conditions and the possible impact of externalities in the absence of substantial scientific information.

The specific objectives of the research are:

1. to develop a bioeconomic model for the potential supply of cultured giant clams from a village farm, which links a biophysical model, that captures the relationships inherent in the giant-clam production system, to market conditions through an economic model;
2. to explore optimal management of the giant-clam farming operation for a villager farming giant clams for the aquarium market and the seafood market;
3. to estimate potential supply of cultured giant clams from Solomon Islands under optimal management conditions; and
4. to illustrate the application of the model to investigate possible externalities imposed by forestry on the giant-clam farming operation.

1.5 Thesis outline

An overview of giant clams and their commercial culture is presented in Chapter 2. Their biology, culture techniques and markets are discussed.

In Chapter 3 the development of giant-clam farming in Solomon Islands is outlined. Solomon Islands is briefly described, a brief history of ICLARM's giant-clam research and development activities is provided and the village-farming trials are described.

A conceptual model for the development of giant-clam mariculture in Solomon Islands is presented in Chapter 4. Central to this model is the potential supply of cultured giant clams from a village farm, which is described using a bioeconomic approach.

In Chapter 5 a mathematical description of a bioeconomic model for the potential supply of giant clams from a village farm is presented. The model comprises economic and biophysical models. The economic model describes the costs and revenues associated with farming a giant-clam population from planting through to harvest. The biophysical model describes the average growth of an individual giant clam and survival within the population. The growth model is a dynamic simulation model that captures the effect of environmental and management variables. Management variables include husbandry, which refers to the amount of cleaning, and the frequency with which thinning is undertaken. Survival is described by a simple decay function.

In Chapter 6, the economic and biological data required to simulate the performance of the giant-clam production system and to explore optimal farm management are described. The economic variables affecting giant-clam farm profitability include production costs (for clam seed, labour, capital and marketing service) and marketable clam prices. Biological variables affect giant-clam farm profitability through clam yield. Growth, survival and environmental data collected from ICLARM's village-farming trials are described.

The growth model for an individual giant-clam is analysed in detail in Chapter 7. Calibration and validation of the model are discussed and simulated growth is compared with actual growth data from ICLARM's village-farming trials. The sensitivity of the model to biological and environmental parameters and the effect of husbandry and thinning frequency on growth predictions are investigated. The input substitutability between labour and time in the production of clams of a particular target size is investigated.

The bioeconomic model is applied in Chapter 8 to explore optimal management of the giant-clam farming operation. The model is solved for a single clam harvest and multiple harvests for various management scenarios involving different combinations of husbandry and thinning frequency. Optimal management results for cycle-length, profit, labour, harvest and shell length of the clams at harvest, are presented for each management scenario for the multiple-harvest case. The input substitutability between labour and cycle-length is further investigated. The potential supply of cultured giant clams from Solomon Islands is then estimated under optimal management conditions and assumptions regarding adoption rates.

In Chapter 9, the model is used to investigate the possible externalities imposed by forestry, through sedimentation, on optimal management of the giant-clam farming operation. Sediment run-off may increase turbidity and nutrients in the seawater in which giant clams are farmed. The effects on simulation results of different combinations of turbidity and nutrient deposition are investigated, and the marginal costs and benefits of sedimentation are estimated.

Finally, conclusions are drawn in Chapter 10. The conceptual model presented in this thesis for the development of commercial giant-clam mariculture will help with research planning and evaluation and policy analysis of the emerging industry. The bioeconomic model for the potential supply of giant clams from a village farm, which is at its core and which is developed and applied in this study, can be used to estimate optimal management strategies for village farmers. The model allows simulation of the production and profitability of several commercial giant-clam species at different locations, although only two species farmed in Solomon Islands are considered here. The model can be used to provide insight into potential industry supply and the effect of externalities that may be imposed by forestry on optimal management of giant-clam farming.

The author knows of no other study that simulates the giant-clam production system from planting through to harvest using this type of detailed bioeconomic approach.

2. Overview of giant clams and their commercial culture

In this chapter, the biology of giant clams, the longest established technique for their culture, and the markets identified so far for cultured giant-clam products are described.

2.1 Biology of giant clams

Giant clams are marine bivalve molluscs of the family *Tridacnidae* (Govan, 1995). Nine extant species have been described in two genera, *Tridacna* and *Hippopus*. They are *Tridacna crocea*, *T. derasa*, *T. gigas*, *T. maxima*, *T. rosewateri*, *T. squamosa*, *T. tevoroa*, *Hippopus hippopus* and *H. porcellanus*. ICLARM has identified that six of these species have economic potential (see Bell *et al.*, 1997c). Classification keys to the most common species can be found in Rosewater (1965, 1982) and Lucas (1988).

Giant clams have two main parts, the shell and the soft flesh; the soft flesh is covered by the coloured mantle, with apertures through which seawater flows to the gills and beneath which are other organs (Calumpong, 1992). Characteristics of the shell and mantle differentiate the species. For example, *T. gigas* may grow to over one meter in shell length and has a predominantly brown mantle, while *T. crocea* grows to only about 15 cm and has a mantle with bright colours, including green, blue, purple and orange.

Giant clams are hermaphrodites capable of spawning both sperm and eggs at full sexual maturity (Lucas, 1988). Their fecundity is very high and they may spawn throughout the year. Fertilised eggs hatch into larvae which undergo several stages of embryonic development culminating in their metamorphosis from swimming larvae into juvenile clams some 2-3 weeks following spawning (Govan, 1995). Metamorphosis involves a number of complex anatomical, behavioural and physiological changes after which the giant clam lives a benthic (bottom-dwelling) mode of life (Heslinga *et al.*, 1990).

During metamorphosis giant clams develop a symbiotic relationship with algae called zooxanthellae, which reside within their mantle tissue and convert sunlight through photosynthesis into nutrients for the clam (Fitt, 1993a). Giant clams also filter-feed from seawater flowing through their gills like other bivalves; however, they are essentially autotrophic, potentially capable of satisfying their daily energy and growth requirements through photosynthesis (Klumpp *et al.*, 1992; Fitt, 1993a). This symbiosis is unique among bivalves and has a profound effect on the ecology of giant clams (they are only found in shallow waters of the Indo-Pacific region) and on their morphology, which is such that their mantle is presented uppermost to the sun (Lucas, 1988).

2.2 Culture techniques

A variety of techniques for the culture of giant clams have been developed, and are documented comprehensively in culture manuals (eg. Heslinga *et al.*, 1990; Braley, 1990, 1992; Calumpong, 1992; Lucas, 1994). The longest established technique involves the culture of giant-clam seed for approximately one year in land-based facilities, followed by transfer to the ocean for grow-out (Tisdell and Menz, 1992). This method is described here. Four main phases may be distinguished: hatchery phase, land-based nursery phase, ocean-nursery phase, and ocean-grow-out phase. Each phase is discussed in turn.

2.2.1 Hatchery phase

Broodstock giant clams are induced to spawn using external stimuli such as hormone injections, or temperature shocks, and they may also spawn spontaneously. Eggs and sperm are collected and mixed so that fertilisation may occur. Fertilised eggs are stocked in larval rearing tanks where they hatch into larvae, metamorphose and settle. Larvae are provided with flowing filtered seawater, and inoculated with antibiotics and zooxanthelae. They may also be fed extraneous feed (eg. algae, yeast, or microencapsulated formulas). The larval rearing tanks may be placed under shadecloth, and the seawater flowing through them may be aerated and have its temperature controlled. Once the larvae have metamorphosed and settled, they are transferred to the land-based nursery phase.

2.2.2 Land-based nursery phase

Recently settled juvenile giant clams are placed in outdoor land-based nursery tanks. Once they have firmly attached to the tank's bottom they are provided with flowing seawater that may be filtered and aerated. Artificial nutrients may be given to enhance growth; however, a high concentration of nutrients may also promote algal fouling. Herbivores (eg. trochus, parrotfish or hermit crabs) may be placed in the tanks to control algal fouling. Juvenile giant clams may be maintained in this phase until they reach 2-2.5 cm in shell length; this requires up to 6-12 months culture depending on the species and environmental conditions.

2.2.3 Ocean-nursery phase

Juvenile giant clams, called seed clams, are placed in protective mesh cages on the sea floor or on trestles elevated above the sea floor in intertidal or subtidal areas of the inshore reef, or suspended near the water surface from floats. Substrates such as coral pieces, stones and cement may be provided to aid attachment. The cages must be regularly checked for predators and to control fouling organisms. Giant clams remain in this phase until they reach 15-20 cm in shell length after which they are considered virtually free from predation and able to withstand environmental stresses.

2.2.4 Grow-out phase

In the grow-out phase the protective mesh cages in which the large juvenile giant clams have been growing are removed and the clams are reared directly on the sea floor. Grow-out sites must be carefully selected to ensure good growth and survival (eg. shallow water depth, high salinity and few predators), and should be visited frequently to check for the effects of environmental disturbance and predation. Depending on the species being cultured and the markets targeted, some clams may be harvested prior to the grow-out phase, while for others grow-out may take several years.

2.3 Markets

The marketing opportunities that exist for cultured giant-clam products have been described by many authors including Dawson (1986), Dawson and Philipson (1989), Heslinga *et al.* (1990), Shang *et al.* (1991), Braley (1992), Calumpong (1992), Tisdell (1992) and Tisdell *et al.* (1994a). The three main markets identified so far are for aquarium specimens, seafood and shells. It is these markets which are considered here.

2.3.1 Aquarium specimens

Cultured giant clams are suitable for the tropical marine aquarium market. They are particularly prized for their colourful mantles. Sales of cultured giant clams to this market commenced in 1987 (Heslinga *et al.*, 1988; Bell *et al.*, 1997c). Since then, the market has expanded steadily, due to increasing demand for protection of endangered populations (Bell and Gervis, 1999; Bell *et al.*, 1997c). The aquarium market is based mainly in the USA and Europe, particularly Germany. Individuals of 5-10 cm in shell length are in greatest demand (Bell, 1997, pers. comm.). Aquarium clams can be reared to market size in less than 2 years at village farms (Bell *et al.*, 1997b; Bell *et al.*, 1997c; Foyle *et al.*, 1997; Hart *et al.*, 1998). The aquarium market is the only active market to date for cultured giant clams (Gervis *et al.*, 1995). The preferred species is *T. crocea*.

2.3.2 Seafood

All the flesh of the giant clam can be consumed as seafood. Markets based on wild stocks existed in Asia for the adductor muscle and in Okinawa, Japan for the whole meat (minus the kidney) for sashimi. Small remnant markets still exist in Hong Kong, Taiwan and Okinawa for these products (Calumpong, 1992). The species traditionally traded are the two larger species for the adductor muscle, and the two smaller species for sashimi. Farming *T. gigas*, the largest species, for the adductor muscle market has not yet been achieved, and its economic viability is dubious (Hambrey and Gervis, 1993; Bell *et al.*, 1997a). However, there is current interest in the potential of cultured *T. derasa* for this market (Bell, 1997, pers. comm.). To supply this market, clams may require 6-10 years grow-out at village farms. Markets with shorter production lags may also have good prospects. The sashimi market in Okinawa, and the live-clam trade in Hong Kong and Taiwan can be supplied with clams of 15 cm in shell length, which can be produced within 2 years at village farms (Bell and Gervis, 1999; Bell *et al.*, 1997c). The species that has the best potential for the seafood market is *T. derasa* (Bell *et al.*, 1997a; Hart *et al.*, 1999).

2.3.3 Shells

The shells of giant clams may be used for a diversity of ornamental and utilitarian purposes, ranging from jewellery to floor tiles. The shell market was once a significant international market, with trade in Japan, USA, Europe, Philippines and Australia, but it withered during the 1980s due to the depletion of wild stocks and the CITES listing. The species most highly prized were *H. hippopus* and *T. squamosa* (Juinio *et al.*, 1987; Calumpong, 1992). Giant clams have not yet been seriously cultured for the shell market although limited sales have taken place (Battaglene, 1997, pers. comm.). Recently there has been increasing interest in the prospects of this market given the need to increase the number of products that can be derived from cultured giant clams (Bell, 1997, pers. comm.). The production of shells for this market will necessarily be linked to the production of clams for seafood, and the production lag will be between 2 and 10 years depending on the level at which the seafood market is targeted.

3. Giant-clam mariculture in Solomon Islands

In this chapter, a brief description of Solomon Islands is provided, with focus on village life. Some villagers are engaged in ICLARM's giant-clam farming trials, and a brief history of ICLARM's involvement in giant-clam research and development is provided. The village-farming trials are then described.

3.1 Solomon Islands

The following features of Solomon Islands are described in turn: geography, climate, population, economic activity, social structure and the role of giant clams. This information is drawn from Leary (1992), and a range of internet sites including Nations of the Commonwealth (www.tbc.gov.bc.ca/cwgames/country/Solomon/), Solomon Islands Demographics (www.tcol.co.uk/solomon/), Solomon Islands Guide to Investment (www.solomon.emb.gov.au/), The World Bank (www.worldbank.org/data/countrydata), The World Factbook 2000 (www.odci.gov/cia/publications/factbook/), and The United Nations (www.un.org/cgi-bin/pubs/infonatn).

3.1.1 Geography

Solomon Islands is situated in the southwest Pacific, roughly between latitudes 5° and 13° south and longitudes 155° and 170° east It is one of the largest archipelagoes in the region, comprising a scattered double chain of six major and nearly 1,000 smaller islands, atolls and reefs. It extends over 1,500 km in a southeasterly direction from Bougainville Island in Papua New Guinea towards Vanuatu. The islands range from large, rugged and mountainous landmasses covered in dense rainforest, to small, bare, low-lying coral atolls. Most of them have a thin coastal belt of coconut trees and mangroves, and coral reefs and lagoons encircle many. Solomon Islands covers over 1.35M km^2 of sea, and has a total land area of 27,560 km^2. It has 9 provinces; the capital Honiara is located on the island province of Guadalcanal. A map of Solomon Islands is presented in Chapter 6.

3.1.2 Climate

The country's proximity to the equator means Solomon Islands has a typically tropical climate, with relatively high and uniform temperatures, high humidity and high rainfall. Daily temperature ranges between 22° C to 31° C throughout the year, humidity regularly reaches 90 per cent particularly in the mornings, and mean annual rainfall normally exceeds 3,000 mm. Daylight lasts about 12 hours per day; sunrise and sunset are around 6.30am and 6.45pm respectively, and dusk is very short. There is significant regional variation in the climate however, due to the diverse nature of the geography. There are also two seasons, the wet and the dry, which last from November to April and May to October, respectively. The wet season is generally characterised by monsoonal winds, higher temperatures, humidity and rainfall. On average there is at least one cyclone in Solomon Islands each year, which tend to occur during the wet season. Cyclones can cause considerable damage to villages, crops, water supplies and rainforests, and lives can be lost. Solomon Islands also experiences constant seismic activity, including earthquakes and volcanoes, because it forms part of the Pacific "Ring of Fire", lying at the boundary of the Pacific and Australian tectonic plates. The last major earthquake was in Guadalcanal in 1977, while the last violent volcanic eruption was in Temotu Province in 1971.

3.1.3 Population

The population of Solomon Islands is estimated to be around 400,000, of which the majority are Melanesian (95 per cent), the remaining 5 per cent are Polynesian, Micronesian, Asian and expatriates of Caucasian descent. Linguistic evidence is that at least 65 indigenous languages are spoken, some of which have very few speakers. The national language is Solomon Islands Pijin, or "broken" English which is spoken by most of the population. There is also a richness and diversity of culture, traditions and customs. The population is growing at an annual rate of 3.5 per cent, which is one of the highest in the world, while the overall population density is less that 15 people per km^2, which is one of the lowest in the Pacific. About 80 per cent of the population is rural, living in some 6,500 small villages on about 350 islands. The average size of a village is about 45 persons. The urban population is confined largely to Honiara and the provincial capitals, and is growing rapidly due to urban drift. About 10 per cent of the population lives in Honiara, this is growing by nearly 10 per cent per annum. The population is young, with 50 per cent below 20 years of age. Education is low, with 40 per cent of the population having never attended school, 50 per cent having at least one year of primary education, 9 per cent having at least one year of secondary education, and only 1 per cent with higher education above secondary school level. English is taught at many schools.

3.1.4 Economic activity

The Solomon Islands economy is largely subsistence. This is reflected in the small number of wage and salary earners, who represent less than 10 per cent of the population. Those earning wages are employed by national and provincial governments and private companies, and are engaged in industries such as agriculture, forestry and logging, fishing, mining and manufacturing, electricity and water, construction, trade, transport and communication, finance and administration. The greater proportion of the population (around 90 per cent) is engaged in subsistence food production and unpaid village work, such as gardening, food collection, fishing, preparation for village ceremonies, maintenance of village tracks, and construction of church buildings and water supplies. The gross domestic product (GDP) of Solomon Islands is estimated to be about US$350M, and growing by nearly 10 per cent per annum. The agricultural sector contributes around 40 per cent to GDP, followed by forestry and fisheries (10 per cent); manufacturing contributes less than 5 per cent. Exports comprise a narrow range of primary and processed products while imports vary over a wide range. Timber and fish have traditionally been the two largest export earners, generally contributing over 60 per cent to foreign exchange earnings. Foreign aid is estimated to be about 25 per cent of GDP.

3.1.5 Social structure

The overwhelming social feature of Solomon Islands is village life. Most villages are located on the coast, close to a freshwater source Villagers live traditional lifestyles, reliant on land and marine resources to satisfy their basic needs and occasionally earn a modest cash income. Villagers have coconut plantations for copra production, gardens for growing fruit and vegetables, and livestock such as chickens and pigs. They harvest traditional foods such as nuts, ferns and fruits from the bush, and collect material for leaf-house and canoe construction, rope and basket weaving, and firewood. They fish and collect shells and other marine products for decoration, ornaments and tools. Villages comprise members of an extended family, close friends and their families, called "wantoks" (ie. of the same "one-talk" or language). Custom requires that wantoks share all their goods and property. Tenure of village land and marine resources is communal and governed by customary law. Disputes are settled by the village chief, who is appointed through patrilineal inheritance, matrilineal inheritance or the bigman cult (ie. through being particularly influential in the village), and is responsible for all aspects of village life. Women usually take on a traditional role in the village. They are responsible for child rearing, gardening and domestic duties, although heavier duties may be undertaken by men. In larger villages, there is always a church (95 per cent of Solomon Islands is devoutly Christian), and often a primary school and a store Sometimes there is a medical clinic and a police station.

3.1.6 The role of giant clams

Giant clams are of traditional importance to villagers in Solomon Islands (Hviding, 1993). They are eaten for food and the shells are used for a variety of ornamental, decorative and utilitarian purposes. Giant clams also have religious and spiritual significance. Solomon Islands has relatively good wild stocks of six species, namely *T. crocea*, *T. derasa*, *T. gigas*, *T. maxima*, *T. squamosa* and *H. hippopus*, from which villagers may harvest. Some villagers are engaged in ICLARM's giant-clam farming trials.

3.2 Brief history of ICLARM's giant-clam research and development activities

ICLARM became involved in giant-clam research when ACIAR funded a major multinational project, "The culture of giant clam (*Tridacna sp*) for food and restocking of tropical reefs", Phase One and Phase Two (ACIAR Project Nos. 8332 and 8733) from 1983 to 1992. James Cook University of Northern Queensland coordinated this project in collaboration with ICLARM. It was scientific and technical in nature and designed to provide information for the development of culture techniques, particularly for the production of large giant clams suitable for the adductor muscle market. The largest species, *T. gigas*, was primarily targeted, although techniques to successfully culture all species were developed. This research did not result in viable techniques for farming giant clams at coastal villages (Bell, 1997, pers. comm.). A substantial body of this research is documented in Copland and Lucas (1988) Braley (1992), Calumpong (1992), Norton and Jones (1992), Fitt (1993a), Munro (1993), and Lucas (1994).

ICLARM's major contribution to this multinational project was the development of a Coastal Aquaculture Centre (CAC) in Solomon Islands (Govan, 1995). The CAC was constructed in 1987 at Auriligo, about 30 km west of Honiara on Guadalcanal. Up until late-1999, ICLARM conducted a giant-clam mariculture project from the CAC, aimed at developing viable small-scale commercial aquaculture of giant clams and the restocking of the larger species. The CAC was then de-commissioned due to civil unrest, and the project moved to ICLARM's more recently constructed field station at Nusa Tupe in the Western Province. The project is funded from ICLARM's core budget and supplemented by grants received from international donors including ACIAR, the European Union, the Economic and Social Commission for Asia-Pacific and the Food and Agriculture Organisation, as an activity within its Coastal Aquaculture and Stock Enhancement Program.

The focus of ICLARM's giant-clam mariculture project has been a set of village-farming trials where selected villagers rear giant clams in ocean nurseries for commercial sale and experiments. The trials are designed to identify the optimal environmental conditions and farming techniques for village farming, and are based on the production of giant clams to test and develop new and existing markets. ICLARM first began hatchery operations to produce the seed clams for the trials in 1987, trials were underway by 1989 (Govan, 1993) and commercial sale of cultured giant-clam products commenced in 1994 (Battaglene, 1997, pers. comm.). Results of the trials are the subject of ongoing publications, eg. Govan (1993), Hambrey and Gervis (1993), Bell (1999a, 1999b), Bell *et al.* (1997b), Foyle *et al.* (1997) and Hart *et al.* (1998, 1999). The trials are discussed in the following section.

Between 1989 and 1994 ICLARM undertook village-farming trials with several species of giant clam. These trials were used to identify suitable techniques for village farming, to train and review the competence and commitment of villagers (Govan, 1993), and to assess the economic viability of village farming for the adductor muscle market and the aquarium market. Hambrey and Gervis (1993) established that farming *T. gigas* for adductor muscle was unlikely to be economically viable, while Bell *et al.* (1997b) and Foyle *et al.* (1997) showed that farming *T. gigas* and *T. squamosa* for the aquarium market was economically viable.

In 1994 ICLARM received funding from the European Union's STABEX Farmer Support Program, for the project "Scaling up production of cultured giant clams at coastal villages in Solomon Islands" (Bell, 1997, pers. comm.). This funding assisted ICLARM with further village trials to assess the viability of farming three more species, *T. crocea, T derasa* and *T. maxima*, for the aquarium market and/or seafood markets. This funding continued until 1997. During 1995-96 ACIAR also contributed to this project through a small grant, "Large-scale village grow-out trials for giant clams" (FIS/95/42), which funded the collection and analysis of data from the village trials (see Hart *et al.*, 1998, 1999). The results demonstrated the biological and economic viability of farming all three species, particularly *T. derasa*, at coastal villages for the aquarium market (Hart *et al.*, 1998). The aquarium market is limited in size however, and unlikely to be large enough to support commercial culture in a variety of developing countries (Bell *et al.*, 1997a, 1997c). Thus, large-scale adoption will depend on expansion of the seafood market.

ICLARM is trying to expand the markets for cultured giant clams as live seafood in Asia and as sashimi in Okinawa. ICLARM commenced village-farming trials with *T. derasa* for live seafood in 1996, to provide sufficient quantities of large clams to test and develop this market, and undertook research to facilitate their transport and marketing (Bell *et al.*, 1997a, 1997c). ICLARM and the Economic and Social Commission for Asia-Pacific (ESCAP) commissioned a marketing consultant to promote the product in Hong Kong and Taiwan (Bell *et al.*, 1997a; Riepen, 1998). A position has been funded by the Food and Agriculture Organisation South Pacific Aquaculture Development Program (FAO SPADP) to organise the distribution of these clams from the farmers to the exporter. The FAO SPADP is assisting ICLARM to identify sashimi markets in Okinawa; in 1997 ICLARM was proposing to commence further village trials with *T. derasa* for this market (Bell, 1997, pers. comm.).

ICLARM has also been looking to undertake additional research to diversify the range of cultured giant-clam products and to add value to the existing products produced by village farmers (Bell, 1997, pers. comm.). ICLARM has prolonged an existing village trial to assess the viability of farming *T. derasa* for the adductor muscle market and for large shells. Research to determine how to consistently produce *T. maxima* and *T. crocea* with irridescent colours for the aquarium trade, and how triploidy may increase the size of the *T. derasa* adductor muscle for clams sold as seafood, has also been planned.

In 1997 ICLARM commenced the project "Impact of giant clam productivity enhancement research" using core funding, as an activity within its Policy Research and Impact Assessment Program (PRIAP). This project is designed to assess the impact of commercial giant-clam research and development activities, and to improve policy decisions, including investments in research. The research presented in this thesis forms part of that project.

3.3 ICLARM's village-farming trials

Gervis *et al.* (1995) and Bell *et al.* (1997c) describe ICLARM's approach to the village-farming trials. ICLARM produces the seed clams for the trials at its hatchery facility at the CAC, and sells them to the village farmers for grow-out. ICLARM undertakes regular farm visits to monitor the growth and survival of the seed and to encourage farmers to embrace good farming practices; it also coordinates the buy-back of clams from farmers once they reach marketable size for sale to local exporters. ICLARM may use the clams for experiments aimed at improving growth, survival and farming techniques.

ICLARM produces about 150,000 seed clams per year for the village trials (Bell, 1997, pers. comm.). These seed clams belong to the six species occurring naturally in Solomon Islands. Most seed are reared through the land-based nursery phase at the CAC, although some are transferred to Paruru Aquaculture, when they are newly metamorphosed larvae, for this phase of the culture cycle. Paruru Aquaculture is a privately owned company established in 1994 in Marau Sound, Gaudalcanal, about 90 km east of Honiara and 120 km from the CAC (Oengpepa, 1994).

ICLARM currently distributes seed clams to some 30 village farmers. Some are "aquarium farmers" (recruited during 1989-92) and others are "meat farmers" (recruited in 1996). The former have been involved in experiments on and production of all six species of giant clams for the aquarium market, the later are involved in the production of *T. derasa* for the live seafood market. Govan (1993) describes the design and initial implementation of the trials, while Gervis *et al.* (1995) describe the criteria more recently used for the selection of village farms.

A map of Solomon Islands showing the locations of the village-farming trials used in this study is presented in Chapter 6. Village farms are located in the Central Province (around Russell Islands and Florida Islands), Guadalcanal Province (in Marau Sound) and Western Province (near Nusa Tupe and around Seghe and Batuna in the Marovo Lagoon). Aquarium farmers are located in all three Provinces, while meat farmers are only in the Central and Guadalcanal Provinces. Meat farmers have not been established in the Western Province due to the prohibitive cost of freighting live *T. derasa* of 15 cm in shell length from this remote location, and the transport cost involved (Lane, 1997, pers. comm.). A farm coordinator is appointed to each area, to oversee activities and to ensure village farmers receive a range of extension services including training, farm visits and newsletters.

ICLARM has undertaken a number of experiments with the aquarium farmers to investigate the effect of environmental conditions and farming protocols on the growth and survival of the various species. These experiments are the subject of ongoing publication (eg. Bell *et al*, 1997b; Foyle *et al.*, 1997; Hart *et al.*, 1998). They have established that *T. derasa* is the outstanding species for village-based farming of giant-clam seafood (Bell, 1997, pers. comm.). ICLARM has been trialing this species with the meat farmers to target the live seafood market. ICLARM is also seeking to trial *T. derasa* for the sashimi market, and is monitoring its morphometrics to establish its suitability for the adductor muscle market.

ICLARM has been regularly purchasing giant clams from village farmers for the aquarium market since 1994 (Battaglene, 1997, pers. comm.). Sales to this market throughout Europe and the USA are made through a local exporter, Solomon Island Marine Exports, and average 20,000-25,000 clams per year (Bell, 1997, pers. comm.). ICLARM has demonstrated the economic viability of farming five species for this market (Bell *et al.*, 1997b; Foyle *et al.*, 1997; Hart *et al.*, 1998). Since 1997, ICLARM has also been purchasing small quantities of giant clams from the meat farmers for marketing trials as live seafood in Beijing, Hong Kong and Taiwan (Battaglene, 1997, pers. comm.). Sales to the live seafood market are also made through Solomon Island Marine Exports given their experience exporting live clams. Bell *et al.* (1997a) describe the transport and marketing considerations of supplying this market. ICLARM has also purchased *T. derasa* from the meat farmers for a few marketing trials as sashimi in Okinawa (Battaglene, 1997, pers. comm.). ICLARM sells to this market through another local exporter, Island Seafoods Ltd, which has considerable experience in the export of raw fish.

3.4 Village farming

Giant-clam farming is undertaken at reef sites adjacent to the farmer's village, for easy access and security against poaching, using simple, low-cost and low-input technology. The typical village farm consists of a collection of cages and trestles. Cages are made from galvanised wire mesh with a concrete bottom and a galvanised wire mesh lid, into which giant clams are stocked for the ocean-nursery phase of culture. Cages are placed on top of trestles made from iron reinforcing rods. Trestles are raised above the sea floor such that the cages are 1-2 m below the water surface at low tide. Trestles are designed to support 4 cages. Tafea (1993) and Lane (1995) describe the design and construction of cages and trestles. A maximum manageable farm size is 70 cages (Gervis *et al.*, 1995). Clams can also be reared in enclosures where cages are placed on the reef floor and covered by a protective mesh, but this is not common practice. Once the clams are large enough to be virtually free from predation and able to withstand environmental stresses, they are placed directly on the sea floor without protection. The use and cost of capital is discussed in more detail in Chapter 6.

3.4.1 Farming activities

The main activities undertaken by giant-clam farmers are planting, cleaning, thinning, and harvesting. Cages and trestles (and enclosures, if they are in use) must also be constructed and maintained. Each of these activities is considered in turn below. Cleaning and thinning should be routinely undertaken each week, planting and harvesting can be undertaken less frequently as required. For an established farm of 70 cages, three half-days per week are recommended (see Govan, 1993; Gervis *et al.*, 1995; Bell *et al.*, 1997b; Foyle *et al.*, 1997). In this time a farmer should achieve good clam growth and survival, and still have sufficient time to undertake subsistence and other income-earning activities. The use and cost of labour for each of these activities is discussed in more detail in Chapter 6.

Planting

Seed is typically distributed to village farmers in batches of 1,000 clams of 2-2.5 cm in shell length. Seed is packed and transported in insulated portable coolers as described by Bell *et al.* (1997a). Aquarium farmers normally receive three such batches per year. When the meat farms were established in 1996, they each received one batch of 3,000 seed clams. If the marketing of *T. derasa* for the live seafood market is successful, meat farmers will likely receive one such large batch per year (Bell, 1997, pers. comm.). Planting requires farmers to transfer seed from the coolers in which they arrive to cages. Seed are planted at a density of 200-250 clams per cage, 1,000 seed are therefore planted into 4-5 cages. Cages may be placed in calm, shallow water adjacent to the farm site for a few days, to allow the seed to attach firmly to the concrete base, before they are transferred to trestles. It may take a farmer more than two hours to plant 1,000 seed clams (see Section 6.2.2). The price farmers pay for seed is set in accordance with a schedule prepared by Gervis (1995); this schedule is presented in Table 6.1. The cost of seed is initially borne by ICLARM, and the seed provided to farmers on credit. The farmers repay the debt from the revenue they receive from clam sales.

Thinning

As the clams grow, they tend to crowd the cages into which they have been planted. Crowding can result in the stunting of clam growth whereby the shell grows thick compared to its length (Lane, 1997, pers. comm.). Village farmers must therefore thin the clams as space in the cages becomes limiting. Thinning means reducing the number of clams per cage (by increasing the number of cages on the farm) as the clams grow. Thinning can be required within three months of planting, depending on the growth and mortality of the clams in the cages. The frequency with which thinning should be undertaken is further discussed in Chapter 6. Clams from the same planting may not necessarily grow at the same rate, so farmers are encouraged to undertake grading while thinning, and place clams of similar size in the same cages. Grading improves growth, since clams of a similar size grow better together, and increases the ease of harvesting. Thinning provides farmers with the opportunity of maintaining an inventory of their clam stock. Farmers are required to give a stock inventory to their farm coordinator every three months.

Cleaning

Cleaning is undertaken to remove algal build-up and predators from the cages. Algal build-up reduces the sunlight reaching the clams, and inhibits the flow of water through the cages (Bell *et al.*, 1997b). Since clams rely on photosynthesis and filter-feeding for their nutrition, excessive algal build-up on the cages inhibits their growth. Infestations of predators can quickly develop in the cages, and if undetected, may result in massive mortality, particularly of small clams. Much has been documented about the predators of giant clams (see Govan, 1992, 1995). For clams less than 15-20 cm, predators include carnivorous snails (Cymatium), fish (Wrasse), flat worms and pyramidellids. For clams over this size, predators include puffer fish, trigger fish, sting ray, manta ray, shark, turtle and crab (Tafea and Lasi, 1997, pers. comm.). Sedentary predators should be removed from the cages, while mobile predators should be discouraged from the farm site. Cleaning should commence immediately following planting. During the first month, algal build-up will be minimal, but checks for predators should be made. Cleaning should then be increased until the clams are 15-20 cm when the cages can be left uncovered providing access for grazing fish. It may then be reduced, although regular checks for predators should still be made.

Harvesting

Village farmers harvest their clams following the receipt of an order from their farm coordinator. Orders are drawn up according to the farmers' own stock inventories, and are shared around so the income from the clam sales is spread across as many of the farmers in the program as possible. Only the aquarium farmers are making regular sales at this stage, due to the early phase in the development of the live-seafood market. For the aquarium farmers, harvesting commences within 2-3 months of a batch of seed clams being planted and is completed within the following 1-2 years (Tafea, 1997, pers. comm.). Harvesting requires village farmers to gather clams from their cages, clean them with a scrubbing brush to remove algae and other unsightly growth, and prepare them for transport to the exporter. The farmers are responsible for covering the cost of internal transport and airfreight (see Section 6.2.4). Some ICLARM staff and village farmers consider that the ease of harvesting depends on the species being harvested and whether the cages were graded. *T. crocea* may be more difficult to harvest than the other species due to its burrowing habit, while *T. maxima* and *T. squamosa* have breakable scutes on their shell. The prices farmers receive for marketable clams are set by ICLARM in collaboration with the respective exporters who supply the export markets (see Section 6.2.5). The price is net of marketing margins of 17.5 percent charged by ICLARM and 40 percent charged by the exporters. The income from clam sales is recorded on each farmer's account, and used to offset any outstanding debt for seed and farming materials credited to the farmer.

Construction, repair and maintenance

New cages, trestles and enclosures must be constructed to replace old ones, and to meet additional requirements for planting and thinning. Old cages, trestles and enclosures must be repaired and maintained because the materials used in their construction have a limited life. For example, galvanised wire mesh and concrete last only about 2 years in the ocean, while steel rods last about 10 years. This can be a very time consuming activity for a farmer who has neglected to undertake it regularly and who must make several new cages for planting or thinning in a short period of time, or who has a large number of cages in disrepair.