

## 4. Conceptual Model

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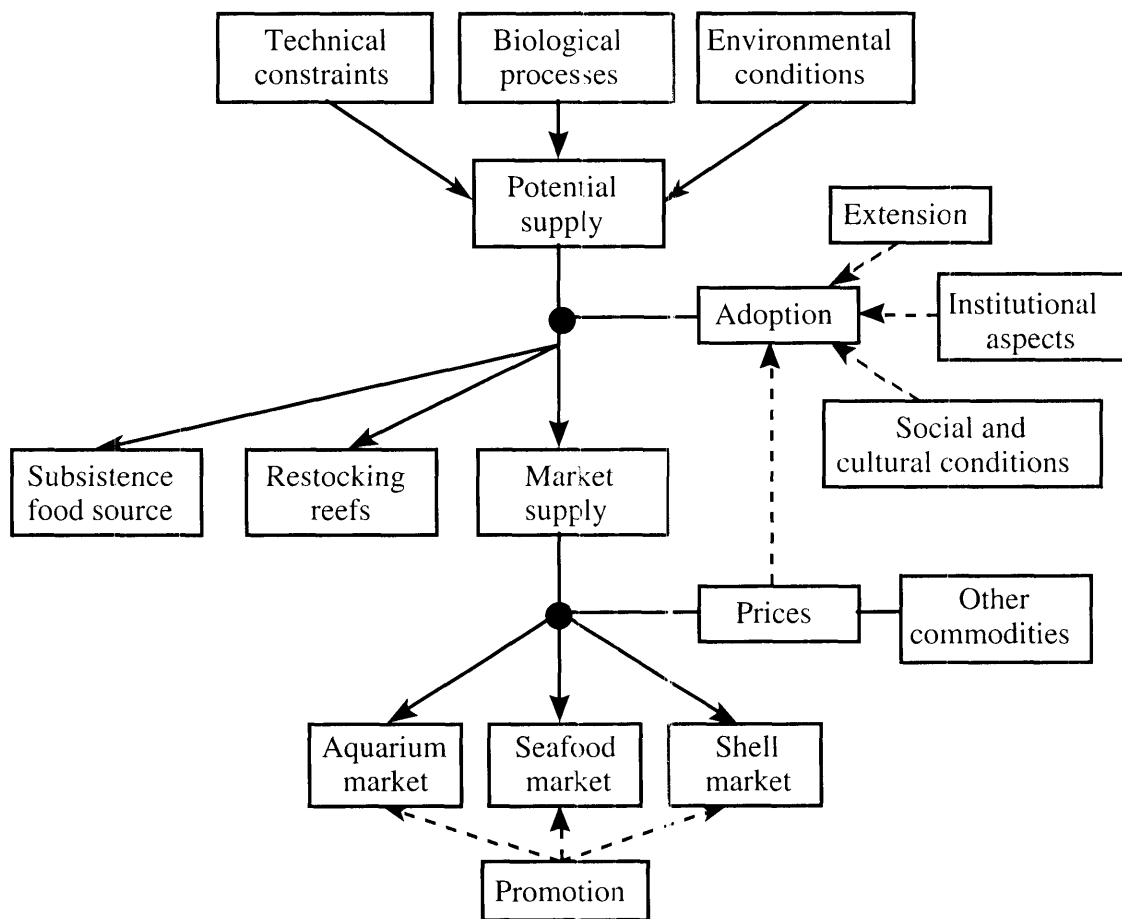
The need for a comprehensive economic evaluation of giant-clam research and development activities to help with research planning and evaluation, and for policy analysis was highlighted in Chapter 1. Past assessments have identified that there are insufficient data available for a proper economic evaluation of the emerging industry (Tisdell, 1991; Kearney and Hundloe, 1998). In this chapter, a conceptual model of the evaluation problem is presented which aims to relax this data constraint by bringing together information available so far into a formal mathematical model using bioeconomic techniques. 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 research and policy evaluation of the emerging industry. It is applied to the development of village-based giant-clam farming in Solomon Islands as a case study. Applications of the bioeconomic model in later chapters demonstrate the contribution it can make to economic analysis and research evaluation of the emerging industry.

### 4.1 Model Description

The conceptual basis to the development of commercial giant-clam mariculture in Solomon Islands may be considered using the model illustrated in Figure 4.1. This model includes both demand and supply aspects of village-based farming, and incorporates relevant biological, environmental, technical, sociological and economic information. Central to the model is the potential supply of cultured giant clams from a village farm, which is determined by the mariculture technology, and biological and environmental factors. The actual market supply is dependent on the rate of adoption of the mariculture technology by potential village farmers, the state of the markets for cultured giant-clam products, and the rate at which cultured giant clams are redirected into restocking reefs and satisfying subsistence needs.

The potential supply of cultured giant clams from a village farm may be considered within a more detailed submodel involving a bioeconomic approach. This submodel is

illustrated in Figure 4.2. The potential supply is represented by output from a biophysical model that describes the production system. The biophysical model is represented here by submodels of individual giant-clam growth, and of survival of the giant-clam population. The economic model provides the link between the production system, market prices and resource costs. Solving the bioeconomic model permits estimation of potential supply and the profitability of production under different environmental, technical and market conditions.



**Figure 4.1. Conceptual model for the development of commercial giant-clam farming**

The model can be implemented in a computer as either an optimising model or a simulation model. In the optimising model described in Figure 4.2, estimated profits are evaluated iteratively until the performance objective is maximised. The performance objective is generally profit maximisation, but it can be extended to cover other objectives; this is called a normative model. When the model is used in

simulation mode, optimisation is not the objective. The model can be run for any given set of scenarios and the resulting profits evaluated and compared. This is a positive model in economic terms.

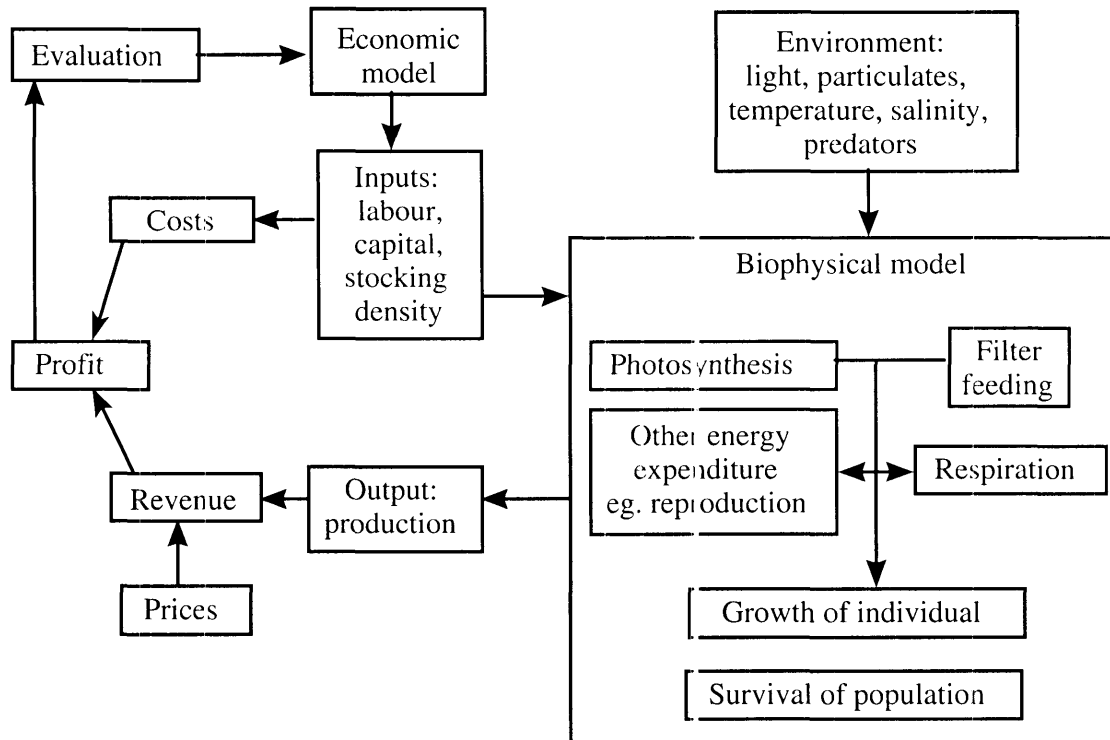


Figure 4.2. Bioeconomic model for the potential supply from a village farm

## 4.2 Application of the model: research and policy

### evaluation

The model described above can be used for evaluation and planning of research and development activities and for policy analysis of the emerging giant-clam farming industry in Solomon Islands. The way in which the model is used depends on the objective of a given evaluation.

For example, the impact of research and development of the production system is evaluated by modifying model parameters at the biophysical level. The effect of genetics research aimed at, for instance, increasing the photosynthetic efficiency of giant clams (and therefore their growth rates), could be evaluated by changing the

shape of the relationship between photosynthesis and irradiance (see equation (5.17) in Chapter 5). This is accomplished by adjusting the value of a biophysical model parameter. In an *ex ante* evaluation, the research cost of modifying, through breeding or genetic engineering, the parameter by a given percentage could be estimated. The actual benefit of this research in terms of growth would then be estimated in dollar terms by using an economic model, such as that shown in Figure 4.2. A similar approach can be followed to estimate the value of developing disease-resistant species. Once the benefits and costs of these two projects are evaluated in dollar terms, they can be directly compared and the project providing the highest net benefit selected. Many other types of research and development projects can be evaluated in this fashion.

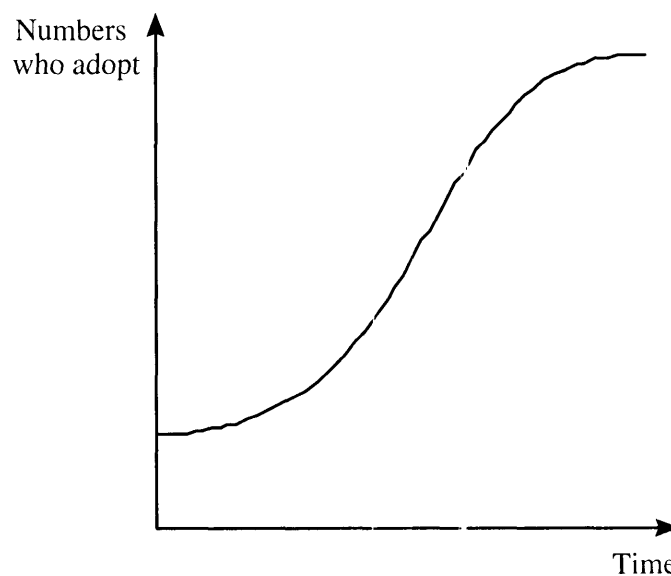
#### **4.2.1 Potential supply**

An important question arising from the example above is the actual definition of benefits. Economists traditionally estimate benefits as the area between the demand and supply curves (producer and consumer surplus). Thus it is common to attempt to estimate these functions statistically based on often very limited data. The biophysical model can be used to estimate potential supply (see Figure 4.1) under a given scenario. This is defined as the maximum supply possible given current technology and resource constraints. Constraints affecting potential supply include the area of suitable fringing reefs, labour and capital availability, transport infrastructure and customary and government regulations.

#### **4.2.2 Actual supply**

The actual supply depends on the rate of adoption of the technology by village farmers. Technology adoption through time is often represented as a logistic function (Figure 4.3), representing an initially slow adoption rate by a few innovative individuals, followed by rapid adoption as more individuals enter the industry, and then a tapering off as full resource use is approached and the industry reaches a mature stage (Griliches, 1958; Alston *et al.*, 1995, p. 30). The length of time to

maturity can be considerable and, in the absence of appropriate institutions and incentives, it may not develop at all. The adoption response depends partly on prices and costs (the attractiveness of the investment) and partly on the availability of information and training of new entrants. For a given level of demand, the adoption rate is influenced by extension activities. This raises a set of questions that requires an interdisciplinary approach: How do different types of extension programs affect the rate of adoption? Why do individuals decide to adopt the technology? What is the opportunity cost of entering the industry? The last question has social implications in the sense that adopting the new technology may affect the contribution that villagers make to traditional subsistence activities. This information can only be obtained through on-site surveys and interviews. Anthropologists and sociologists may be able to help answer these questions.



**Figure 4.3. Logistic function describing possible technology adoption**

### **4.2.3 Demand**

The weakest link in this evaluation framework for giant clams is on the demand side. The long-term growth and survival of the giant clam industry will probably be determined by the demand for giant clams as seafood, because the aquarium market is small by comparison. Practically nothing is known on the demand side of the industry.

An empirical demand analysis will have to wait until enough information has been gathered as the market develops. Meanwhile, through sensitivity analysis it is possible to plan possible research and extension activities by estimating the benefits and costs under alternative (ie. best-case versus worst-case) demand scenarios.

### **4.3 Modelling approach**

Because the giant-clam mariculture industry is still in the early stages of commercial development, production costs, demand factors and the eventual size of the various markets are uncertain. This obviates the application of cost-benefit techniques (Tisdell, 1991) and means it is necessary to adopt a bioeconomic approach.

Bioeconomic modelling focuses on the biophysical and economic components of the system being modelled. A bioeconomic model comprises a biophysical model that describes the production system, and an economic model that links the production system to market prices and resource costs (Cacho, 1997). The economic model controls the behaviour of the biophysical model for its own purposes, and may be normative (optimising) or positive (non-optimising); this will depend on the problem being analysed as indicated in the previous section. The economic model controls factor inputs to the biophysical model and obtains feedback as output. It may be used to predict the effect of environmental and management variables on biophysical processes and to evaluate and compare economic outcomes.

The complexity of the biophysical models that underlie bioeconomic models may vary considerably, depending on the purpose for which they are constructed and the disciplinary bias of the model builder (Cacho, 1998). For example, biophysical models developed by biophysical scientists to closely approximate reality may be very complex, while those developed by economists to yield analytical solutions to economic optimisation problems may be very simple. Biophysical models developed by biologists may be too detailed to be used in optimising economic models designed by economists; conversely, biophysical models consisting of linear or simple non-linear functions designed by economists to allow optimisation problems to be easily solved may be too simple by biologists' standards.

A bioeconomic approach provides the opportunity for interdisciplinary co-operation between biologists and economists, and for decision-making models to be developed that are mutually acceptable within both disciplines (Cacho, 1997). A compromise may be achieved between the simplicity of the model and the ability of the model to approximate reality, and have a unifying effect that makes the total research effort more efficient (Allen *et al.*, 1984; Cacho, 1997). Bioeconomic modelling is therefore an ideal complement to field and laboratory research, where both the model and the research program evolve together (Cacho, 1997; Hatch and Tai, 1997). The model can be used to identify areas where research is likely to yield the most benefits, and the results of new field research can, in turn, be incorporated into the model, making very efficient use of research funds.

A bioeconomic model may be a simple mathematical model for drawing general conclusions about a system, but will more commonly be a fairly complex computer model (Cacho, 1997). Such a model is capable of integrating biophysical principles with economic optimising techniques, using methods of mathematical programming. Stand-alone biophysical simulation models can be used to explore the behaviour of production systems under alternative environmental scenarios and management strategies. However, by embedding them in dynamic optimisation economic models, optimal production strategies can be identified (ie. problems can be solved in which a decision maker wishes to choose the optimal values of a set of management variables over time that minimise or maximise a given objective function) (Cacho, 1998).

Mathematical programming is an optimisation procedure that consists of several techniques, such as linear programming, non linear programming, dynamic programming and goal programming, to solve constrained and unconstrained optimisation problems. These techniques allow for problems to be solved numerically in cases where models are too complex to be solved analytically. Hazel and Norton (1986) and Winston (1991) describe many cases where mathematical programming has been used to solve problems in agriculture and elsewhere. Hatch and Tai (1997) review several studies of aquaculture production systems, of which some use mathematical programming to implement and solve economic models. Mathematical

programming also has potential in research evaluation and planning based on economic-surplus methods (Alston *et al.*, 1995, p. 443).

Allen *et al.* (1984) and Cacho (1997) describe how bioeconomic modelling can be applied to aquaculture production systems. Hatch and Tai (1997) review the principles of aquaculture production economics, including bioeconomic modelling. Bjorndal (1988, 1990) uses bioeconomic modelling to analyse the developing salmon aquaculture industry. These authors consider that the bioeconomic approach is an effective and efficient way in which to design aquaculture production systems and evaluate and plan research programs, particularly when the systems are in the early stages of technical and/or commercial development.

#### **4.4 Summary**

The conceptual model described in this chapter has been developed for research planning and evaluation and policy analysis of the emerging commercial giant-clam mariculture industry in Solomon Islands. It demonstrates the scope that exists for interdisciplinary research, particularly among biologists, sociologists and economists, into this emerging industry. Because possible rates of adoption and the potential growth of the various markets for cultured giant-clam products are unknown, analysis must be of a "what if" type. There is considerable need to undertake this research to document the growth of the industry and the process of market development. This presents an excellent opportunity to develop and test a truly interdisciplinary model for impact assessment and policy analysis. The approach, in fact, constitutes a general model that could be applied to other agricultural and aquacultural systems, since the principles of aquaculture production economics and management are similar to those for other agricultural enterprises (Hatch and Tai, 1997). It would be particularly suitable for analysis of other coral-reef-based activities, such as the culture of hard corals and fish for the aquarium market, since the computer model could be easily adapted to such applications.

The research presented in this thesis covers only part of the problem, as it focuses on potential supply of giant clams by individual producers.



## 5. Mathematical Model

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The mathematical description of a bioeconomic model for the potential supply of giant clams from a village farm is presented in this chapter. The conceptual basis of the model was described in Chapter 4. The theoretical basis described here is the economics of optimal forestry management. 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. Giant-clam production is simulated by the biophysical model and used by the economic model to estimate profitability of the farming system in present-value terms. Production and profitability are affected by environmental and decision variables.

The model is described in an optimising framework. It is applied in later chapters to explore optimal management of the giant-clam operation. Although village farmers may not be profit maximisers, it is of economic interest to undertake a normative study of their production system. Given increasing pressure on villagers to progress from a subsistence lifestyle to a cash economy, profit is becoming more important. Although other behavioural assumptions can be investigated with the model described here, profit maximisation is taken as the only objective in this study, as it provides a benchmark against which current practices can be evaluated.

### 5.1 Theoretical Basis

The theoretical basis of the bioeconomic model for giant-clam farming is found in the economic theory of optimal forestry management (eg. Samuelson, 1976; Comolli, 1981). Its application to giant-clam farming has been well established by the studies of Leung *et al.* (1994a, 1994b). Both giant-clam and forestry operations are characterised by a long delay between planting and harvesting, and the problem is to determine the optimal time between planting and harvesting (the cycle-length).

Assuming that both costs and revenues are incurred at the end of a production cycle, the rules for optimal cycle-length are derived below.

For a single clam-production cycle, the optimal cycle-length is that  $T$  which maximises the objective function:

$$\pi(T) = V(T)e^{-rT} \quad (5.1)$$

where  $\pi(T)$  is the present value of the profit,  $V(T)$ , obtained at the end of a cycle of  $T$  years, and  $r$  is the discount rate. As shown by Hanley *et al.* (1997, p. 337), equation (5.1) is maximised when:

$$\frac{V'(T)}{V(T)} = r \quad (5.2)$$

This states that it is optimal to delay harvest until the specific growth rate in the value of the clams equals the discount rate. Equation (5.2) is sometimes called the Fisher rule (Bjorndal, 1988, 1990; Hean, 1994) for the single-cycle solution. At this point  $T = T^*$ , where  $T^*$  is the optimal cycle-length.

For multiple clam-production cycles, the objective function over an infinite time horizon is given by:

$$\pi(T) = V(T)e^{-rT} + V(T)e^{-2rT} + V(T)e^{-3rT} + \dots + V(T)e^{-\infty rT} \quad (5.3)$$

By the sum of a convergent geometric progression, this simplifies to:

$$\pi(T) = \frac{V(T)}{e^{rT} - 1} \quad (5.4)$$

Manipulating the first-order condition for profit maximisation, yields:

$$V'(T^*) = rV(T^*) + r \frac{V(T^*)}{e^{rT^*} - 1} \quad (5.5)$$

The second term on the right hand side of this equation represents all future clam cycles after the first harvest. It is the opportunity cost of delaying harvest for an additional time period, or the return that could be earned if the current clam crop were harvested and a new one planted.

Equation (5.5) can be manipulated to yield the Faustmann rule, where the proportional increase in the future value of profits equals the discounted value of the interest rate:

$$\frac{V'(T^*)}{V(T^*)} = \frac{r}{1 - e^{-rT}} \quad (5.6)$$

Compared with the solution to the single-cycle problem,  $T^*$  is of shorter duration in the multiple-cycle case. This is because slower-growing older clams can be harvested and replaced by faster-growing younger clams. Anderson (1976) has shown that the general optimal control model converges to this solution.

## 5.2 Bioeconomic Model

As stated above, giant-clam production is simulated by a biophysical model and used by an economic model to evaluate profitability of the farming system. The economic model is described below, followed by a description of the biophysical model.

### 5.2.1 Economic Model

The economic model describes the costs and revenues associated with farming a giant-clam population from planting through to harvest. It is assumed that costs are incurred at the end of the production cycle, when revenues are also obtained. This is not unrealistic, since ICLARM provides clam seed and the materials for cage and trestle construction to village farmers on credit. This also makes exposition simpler. These costs are the “financial” costs from the farmer’s perspective, rather than the total “resource” costs which are incurred by ICLARM. Farmers are not charged the interest cost associated with this advance, which represents an implicit subsidy.

In the model, only one cage of clams is planted at the start of the planning horizon; thinning increases the number of cages on the farm up to a maximum of 16.

The present value of profits from harvesting the clams at time  $T$  (years) is given by:

$$\pi_T = V_T\{h_T, \mathbf{u}, \mathbf{p}\}e^{-rT} \quad (5.7)$$

where  $h_T$  is total clam harvest (kg) at time  $T$  and  $\mathbf{u}$  and  $\mathbf{p}$  are vectors of decision variables and prices, respectively. There are four decision variables: clam-seed size ( $w_0$ , wet weight of tissue plus shell, kg), number of clam seeds planted in the initial cage ( $N_0$ ), husbandry level ( $H$ ), and thinning frequency ( $TF$ , weeks). Thus:

$$\mathbf{u} = [w_0, N_0, H, TF] \quad (5.8)$$

The price vector is:

$$\mathbf{p} = [P_C, P_S, P_L, P_K, P_M] \quad (5.9)$$

where the elements of this vector represent the prices of marketable clams, clam seed, labour, capital and marketing services respectively.

$V_T$  is measured in Solomon Island dollars (SBD\$), and is given by the difference between total revenue ( $R_T$ ), and total cost ( $C_T$ ):

$$V_T = R_T \{h_T, \mathbf{u}, \mathbf{p}\} - C_T \{h_T, \mathbf{u}, \mathbf{p}\} \quad (5.10)$$

$$R_T = \frac{P_C \{w_T\}}{X_r} h_T \{\mathbf{u}\} \quad (5.11)$$

$$C_T = P_S \{w_0\} N_0 + P_L L_T \{\mathbf{u}\} + P_K K_T \{\mathbf{u}\} + P_M h_T \{\mathbf{u}\} \quad (5.12)$$

where  $P_C$  is measured in America dollars (US\$) and  $X_r$  is the exchange rate between US\$ and SBD\$. The labour ( $L$ , hours) and capital ( $K$ , “standard” cages) inputs over the period  $(0, T)$  and the harvest ( $h_T$ ) depend on the decision variables in  $\mathbf{u}$ . Labour is used for planting, cleaning, thinning and harvesting, while capital inputs are measured in standard cages, comprising one cage plus one quarter of a trestle (since a cage takes up a quarter of a trestle). The price of marketing services ( $P_M$ ) includes the cost of internal freight and transport from the village farm to the exporter, while  $P_S$  and  $P_C$  are functions of the initial and final weight of the clams respectively. The data and assumptions for estimation of economic-model parameters are discussed in Chapter 6.

The harvest is given by:

$$h_T = w_T \{\mathbf{u}\} N_T K_T \quad (5.13)$$

where  $w_T$  is the average wet weight (tissue plus shell, kg) of the clams harvested, and  $N_T$  is the number of clams harvested per cage. Both  $w_T$  and  $N_T$  are estimated by the biophysical model (see equations (5.39) and (5.40) respectively).

## 5.2.2 Biophysical Model

The biophysical model describes the average growth of an individual giant clam and survival within the population. The growth component of the model is described in terms of an energy (carbon) budget, in which growth is the difference between energy intake and energy expenditure. Energy intake is from photosynthesis in the form of translocated photosynthate derived by the clam from its symbiotic algae, and absorbed ration from the clam filter-feeding on water containing particulate organic matter. Energy expenditure is for routine respiration (maintenance metabolism) and to satisfy surplus energy demand for unaccounted metabolic processes such as reproduction (Klumpp and Griffiths, 1994; Munro, 1997, pers. comm.). Any remaining energy is allocated to growth, which, of all energy uses, has the lowest metabolic priority.

The survival component of the model describes changes in the number of individuals in the giant-clam population from planting through to harvest. Changes in the population are attributed to mortality alone, with no account given to reproduction, since farmed clams are usually harvested prior to sexual maturity. Survival is described by a decay function and is not affected by environmental or management variables. The reason behind this assumption is explained below.

Time subscripts are eliminated from the mathematical description of the model for clarity of presentation.

### 5.2.2.1 Growth Model

In terms of an energy budget, clam growth is given by the difference between energy intake and expenditure:

$$G = (TP + AR) HE - (RH + SE) \quad (5.14)$$

where  $G$  is clam growth;  $TP$  is translocated photosynthate and  $AR$  is absorbed ration, both measured under ideal husbandry conditions;  $HE$  is a husbandry effect described below; the energy expenditures are routine respiration ( $RH$ ) and surplus energy ( $SE$ ). All variables are measured in mg carbon (C)/day.

Energy intake may be reduced by  $HE$ , which is described by a linear function:

$$HE = 1 - \alpha_H |H - 5| \quad (5.15)$$

where  $H$  refers to the level of husbandry (cleaning) and is measured on a scale from 1 (non-existent) to 5 (excellent). Less than excellent husbandry may result in algal build-up in the clam's cage, which reduces energy intake from photosynthesis through shading, and from filter-feeding through inhibiting water flow (Bell *et al.*, 1997b). Other terms in equation (5.14) are described in the sections that follow.

### ***Photosynthesis***

The amount of photosynthate translocated by the algal symbionts to the clam host ( $TP$ , mg C/day) is given by:

$$TP = [(PA \cdot PQ) - (RC \cdot RQ \cdot k_a)]TR \quad (5.16)$$

where  $PA$  is gross algal photosynthesis (mg C/day),  $PQ$  is the photosynthetic quotient<sup>1</sup>,  $RC$  is respiration of the entire clam (host plus algae, mg C/day),  $RQ$  is the respiratory quotient<sup>2</sup>,  $k_a$  is the proportion of entire clam respiration attributable to the

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<sup>1</sup> The photosynthetic quotient is the ratio of the volume of oxygen produced to carbon dioxide consumed during photosynthesis.

<sup>2</sup> The respiratory quotient is the ratio of the volume of carbon dioxide produced to oxygen consumed during respiration.

algae, and  $TR$  is the proportion of the excess algal photosynthate that is translocated to the host (Klumpp *et al.*, 1992).

Gross algal photosynthesis is described by:

$$PA = DE \cdot \sum_1^{24} P_{\max} \tanh \left( \frac{I_{dhr}}{I_k} \right) \quad (5.17)$$

$DE$  is the "density effect", and is a multiplier on the photosynthesis-irradiance relationship described by the hyperbolic-tangent function (eg. see Mingoa, 1988).  $P_{\max}$  is the asymptote of the hyperbolic-tangent function (ie. the photosynthesis at saturating irradiance) and  $I_k$  is the irradiance at which the initial slope of the function intersects  $P_{\max}$ .  $I_{dhr}$  is the irradiance reaching the clam for each decimal part of the day.  $P_{\max}$  is measured in mg C/hr, while  $I_{dhr}$  and  $I_k$  are measured in MJ/m<sup>2</sup>/hr.

The "density effect" captures the negative effect of crowding in the clam's cage. Crowding reduces the energy intake from photosynthesis, since the clam is not able to fully project its mantle as space becomes limiting. Crowding is attenuated by thinning which involves reducing the number of clams per cage (increasing the number of cages) as they grow.  $DE$  is calculated as a proportion as follows:

$$DE = \frac{CA}{N \cdot MA} \quad (5.18)$$

where  $CA$  (cm<sup>2</sup>) is the cage area,  $N$  is the number of clams per cage, and  $MA$  (cm<sup>2</sup>) is the area taken up by the clam fully projecting its mantle.  $MA$  is given by a power function of tissue dry weight (Griffiths and Klumpp, 1996):

$$MA = \alpha_M TDW^{\beta_M} \quad (5.19)$$



where  $TDW$  is tissue dry weight (g) and is estimated through numerical integration of the model as explained later (see Partitioning).

$P_{max}$  is given by a power function of tissue dry weight as follows (Klumpp and Griffiths, 1994):

$$P_{max} = \Psi \alpha_p TDW^{\beta_p} \quad (5.20)$$

where  $\Psi$  is a function describing the rate of temperature-dependent photosynthetic response, and is described by the O'Neill equation (Spain, 1982):

$$\Psi = \Psi_{max} \left( \frac{Temp_{max} - Temp}{Temp_{max} - Temp_{opt}} \right)^{\eta} e^{\left[ \frac{\eta(Temp - Temp_{opt})}{Temp_{max} - Temp_{opt}} \right]} \quad (5.21)$$

$\Psi$  captures the effect of temperature ( $Temp$ , °C) on  $P_{max}$ , which increases with increasing temperature, up to a maximum at the optimum temperature,  $Temp_{opt}$ , and then rapidly decreases as the lethal temperature,  $Temp_{max}$ , is approached. The constant  $\eta$  is estimated based on the temperature coefficient<sup>3</sup>  $Q_{10}$ , and the optimum and lethal temperatures as follows:

$$\eta = \frac{\tau^2 \left( 1 + \sqrt{1 + \frac{40}{\tau}} \right)^2}{400} \quad (5.22)$$

where:

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<sup>3</sup> The temperature coefficient gives the increase in photosynthetic rate (expressed as a multiple of the initial rate) produced by raising the temperature by 10 °C.

$$\tau = (Q_{10} - 1)(Temp_{max} - Temp_{opt}) \quad (5.23)$$

The environmental variables,  $Temp$  and  $I_{dhr}$ , are given by annual cycles and their calculation is described in a different section (see Section 5.2.2.3).

$RC$ , the respiration of the entire clam (host plus algae, mg C/day), is given by:

$$RC = \Omega \alpha_R TDW^{\beta_R} \quad (5.24)$$

in which  $\Omega$  is a temperature-response function described by a modified Eyring and Urry (1975) equation:

$$\Omega = \frac{\phi_1 Temp e^{(-\phi_2/Temp)}}{1 + \phi_3 e^{(-\phi_4/Temp)}} \quad (5.25)$$

The function  $\Omega$  captures the effect of temperature on respiration rate. Respiration increases with increasing temperature, up to a maximum, and then rapidly decreases as the lethal temperature is approached.

### ***Filter-Feeding***

Absorbed ration through filter-feeding ( $AR$ , mg C/day), the second term in equation (5.14), is expressed as (Klumpp and Griffiths, 1994):

$$AR = IR \cdot AE \quad (5.26)$$

where  $IR$  is the ingested ration (mg C/day) and  $AE$  is the efficiency with which the ingested ration is absorbed;  $IR$  is given by:

$$IR = CR \cdot POC \quad (5.27)$$

where  $POC$  is the particulate organic carbon content of the filtered water (mg C/ $\ell$ ) and  $CR$  is the rate at which water is cleared for filter feeding ( $\ell$ /day):

$$CR = \alpha_f TDW^{\beta_f} \quad (5.28)$$

### ***Energy Expenditures***

The expenditure terms in equation (5.14) include the routine respiratory carbon demand of the clam host ( $RH$ , mg C/day) and surplus energy expended on unaccounted metabolic processes ( $SE$ , mg C/day).

$RH$  is given by (Klumpp *et al.*, 1992):

$$RH = RC \cdot RQ(1 - k_a) \quad (5.29)$$

where  $RC$  (mg C/day), the respiration of the entire clam (host plus algae), was described in equation (5.24) above.

$SE$  is expressed as:

$$SE = SI \cdot SA \quad (5.30)$$

in which:

$$SI = \alpha_E [(TP + AR)HE]^{\beta_E} \quad (5.31)$$

and:

$$SA = 1 + \alpha_A TDW^{\beta_A} \quad (5.32)$$

$SI$  (mg C/day) describes surplus energy as a power function of energy intake, and  $SA$  describes the effect of age on  $SI$ , and is represented by a multiplier that increases at an increasing rate as a function of tissue dry weight.

### ***Partitioning***

Clam growth ( $G$ ) is partitioned between growth of tissue and growth of shell, as described by a carbon-partitioning function,  $CP$ , which gives the proportion of carbon used for tissue growth as a power function of tissue dry weight ( $TDW$ , g dry weight):

$$CP = \alpha_C TDW^{\beta_C} \quad (5.33)$$

The product of  $G$  and  $CP$  gives the growth of tissue,  $GT$ :

$$GT = G \cdot CP \quad (5.34)$$

which, when multiplied by a constant,  $k_d$ , converts growth to grams of tissue dry weight/day ( $d TDW$ ):

$$d TDW = GT \cdot k_d \quad (5.35)$$

Initial tissue dry weight is given by  $TDW_0$ . Subsequent values of  $TDW$  are given by numerical integration of the model.

Shell dry weight ( $SDW$ , g dry weight) and shell length ( $SL$ , cm) are given by power functions of  $TDW$  (Klumpp and Griffiths, 1994):

$$SDW = \alpha_s TDW^{\beta_s} \quad (5.36)$$

$$SL = \alpha_l TDW^{\beta_l} \quad (5.37)$$

$TDW$  is converted to tissue wet weight ( $TWW$ , g wet weight) by dividing by a constant,  $k_w$ , which is the proportion of dry tissue in wet tissue (Klumpp and Lucas, 1994):

$$TWW = \frac{TDW}{k_w} \quad (5.38)$$

Shell is assumed not to absorb water, so  $SDW$  also represents its wet weight equivalent. Total wet weight ( $w$ , kg) is therefore given by the sum of tissue wet weight and shell dry weight as follows:

$$w = \frac{TWW + SDW}{1000} \quad (5.39)$$

This variable provides input to the economic model (see equation (5.13)).

### **5.2.2.2 Survival Model**

Analysis of survival data from a large number of giant-clam village-farming trials in Solomon Islands did not provide conclusive evidence regarding the effects of environmental and management variables on mortality (see Chapter 6). Hart *et al.* (1998) also found regression models for survival were a poor fit to this data. A detailed survival model may have been estimated had other data sources been

explored, but time constraints did not allow this. Hence, it was deemed appropriate to describe the survival of the farmed giant-clam population from planting through to harvest at time  $T$  as a decay function:

$$N = \frac{N_0 e^{-\mu T}}{K} \quad (5.40)$$

$N$  is the surviving number of clams per cage,  $N_0$  is the number of clam seeds planted in the initial cage (ie. the initial population),  $K$  is the number of standard cages on the farm and  $\mu$  is the daily mortality rate (clams per cage per day). Changes in the population are attributed to mortality alone, with no account given to reproduction, since farmed clams are usually harvested prior to sexual maturity. This variable also provides input to the economic model (see equation (5.13)).

### **5.2.2.3 Environmental Cycles**

Annual environmental cycles are included in the biophysical model for temperature and irradiance. Temperature affects photosynthesis (see equations (5.20)-(5.23)) and respiration (see equations (5.24)-(5.25)), while irradiance affects only photosynthesis (see equation (5.17)). These cycles are described in turn.

#### ***Temperature***

Temperature is estimated by a sine function describing the seasonal variation in average daily air temperatures (Charles-Edwards, 1982):

$$Temp = Temp_M + Temp_R \sin \left[ \frac{2\pi (nd + Z - Lut/2)}{365} \right] \quad (5.41)$$

$Temp_M$  and  $Temp_R$  represent the mean annual temperature and the seasonal amplitude (range) about the mean respectively. They are approximated by:

$$Temp_M = 32.5 - 0.45 Lat \quad (5.42)$$

and:

$$Temp_R = Temp_M (0.015 Lat - 0.10) \quad (5.43)$$

where  $Lat$  is °latitude within the range  $10 < Lat < 55$ , the variable  $nd$  is the date of the current time period expressed as the number of days after January 1 (ie. January 1 = 1) and  $Z$  is the date (relative to January 1) at which the autumn equinox occurs.  $Z$  is 101 in the Southern Hemisphere and 283 in the Northern Hemisphere. The constant  $Pi$  has the value 3.1416.

### ***Irradiance***

The irradiance reaching the clam during the day is given by a cosine function describing its diurnal variation (France and Thornley, 1984):

$$I_{dhr} = \frac{I_D}{DL} \left\{ 1 + \cos \left[ (dhr - 0.5) \frac{2Pi}{DL/24} \right] \right\} \quad (5.44)$$

where  $I_D$  (MJ/m<sup>2</sup>/day) is the irradiance penetrating to depth  $D$  (m) and  $DL$  is the daylength (hrs/day). This function applies to each decimal part of the day ( $dhr$ ) in the range:

$$0.5 - 0.5 \frac{DL}{24} \leq dhr \leq 0.5 + 0.5 \frac{DL}{24} \quad (5.45)$$

Outside of this range,  $I_{dhr} = 0$ .

$I_D$  is calculated using Lambert's Law (Boyd, 1979):

$$I_D = I \cdot e^{-X \cdot D} \quad (5.46)$$

in which:

$$X = \frac{1.7}{V_{SD}} \quad (5.47)$$

$I$  is the daily integral of irradiance at the water surface (MJ/m<sup>2</sup>/day) and  $X$  is the light extinction coefficient.  $X$  is inversely related to Secchi disk visibility<sup>4</sup> ( $V_{SD}$ , m), and captures the effect of water turbidity on photosynthesis.

The daily irradiance integral and daylength are described by sine functions of the following form (Charles-Edwards, 1982):

$$I = I_M + I_R \sin \left[ \frac{2Pi (nd + Z)}{365} \right] \quad (5.48 A)$$

$$DL = DL_M + DL_R \sin \left[ \frac{2Pi (nd + Z)}{365} \right] \quad (5.48 B)$$

---

<sup>4</sup> A Secchi disk is a weighted disk, 20 cm in diameter and painted with alternative black and white quadrants. The distance (horizontal or vertical) for which a Secchi disk is visible underwater provides a measure of transparency. The greater the turbidity of water, the smaller the Secchi disk visibility (Boyd, 1979).



$I_M$  and  $DL_M$  are the mean annual values of each variable;  $I_R$  and  $DL_R$  are the seasonal amplitudes (ranges) about their respective means. They may be approximated for each variable by:

$$I_M = 24.3 - 0.264 Lat \quad (5.49)$$

$$I_R = I_M (0.0186 Lat - 0.12) \quad (5.50)$$

and:

$$DL_M = 12.11 \quad (5.51)$$

$$DL_R = \frac{e^{7.42+0.045Lat}}{3600} \quad (5.52)$$

for latitudes within the range  $10 < Lat < 55$ .

The following chapter presents the estimation of parameter values for the model described above.

## 6. Data and Assumptions

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In this chapter, the data used to estimate parameter values for the giant-clam production system model are described. Harvest yields depend on the species being farmed, the management practices of the village farmer and the conditions in the culture environment. Farm profitability is affected by production costs, marketable clam prices and harvest yields. The author collected most of this data while on field research with ICLARM in Solomon Islands during 1997. Where possible it is compared with other data found in the literature. The author is indebted to ICLARM staff and village farmers who provided much of the information.

### 6.1 Species farmed

ICLARM has identified that six of the giant-clam species have economic potential. These are *T. crocea*, *T. derasa*, *T. gigas*, *T. maxima*, *T. squamosa* and *H. hippopus* (see Bell *et al.*, 1997c). It would be difficult to accurately model all these species because several growth parameters in the biophysical model are not reported in the literature and there is insufficient data available with which to estimate them (see Chapter 7). The preferred species for the aquarium market is *T. crocea*, while the species that appears to have the best potential for the seafood market is *T. derasa*. These two species were selected for consideration in this study.

### 6.2 Economic data

The economic variables affecting giant-clam farm profitability include production costs and marketable clam prices. Data was gathered on the input and cost of clam seed, labour, capital and marketing services and used as a guide for determining the production costs of farming *T. crocea* and *T. derasa*. Data was also gathered on marketable clam prices and used to estimate price functions for each species.

### 6.2.1 Clam Seed

Clam seed is produced at the ICLARM CAC and sold to the village farmers on credit (Gervis *et al.*, 1995). Farmers are not charged the interest cost associated with this advance, which represents an implicit subsidy. The price schedule estimated by Gervis (1995) was used (see Table 6.1). Gervis (1995) estimated this price schedule for the hatchery at Paruru Aquaculture in Marau, Guadalcanal, assuming production of 50,000-200,000 seed per year. The price of the seed varies with its age (provided it grows to the minimum shell length expected for its age, also presented in Table 6.1) and ranges from SBD\$0.60 for a 6-month old animal to SBD\$1.61 for a 12-month old animal. Slow growing seed, shorter in length than is expected for its age, is sold at the price that corresponds to its length. This price schedule is used irrespective of the market for which the seed is targeted. Even though prices for seed less than 2 cm long are presented in Table 6.1, ICLARM does not sell seed to farmers until it reaches 2 cm.

**Table 6.1. Prices for clam seed produced by ICLARM**

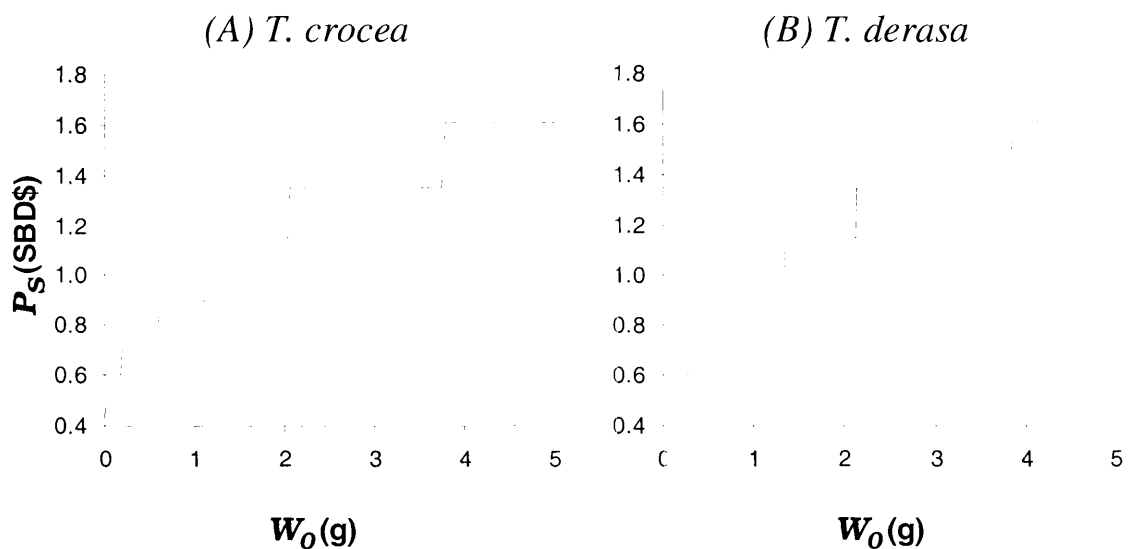
Clam seed age (months)	Price (SBD\$/Seed)	<i>T. crocea</i> (cm)	<i>T. derasa</i> (cm)	<i>T. gigas</i> (cm)	<i>T. maxima</i> (cm)	<i>T. squamosa</i> (cm)	<i>H. hippopus</i> (cm)
6	0.60	0.92	1.48	0.59	1.30	1.41	1.02
7	0.70	1.14	1.72	0.81	1.42	1.59	1.15
8	0.80	1.36	2.00	1.13	1.60	1.69	1.28
9	0.90	1.61	2.37	1.52	1.75	1.92	1.40
10	1.15	1.93	2.80	2.07	1.85	2.16	1.57
11	1.35	2.30	3.22	2.80	2.10	2.33	1.75
12	1.61	2.75	3.84	3.85	2.30	2.53	1.96

The prices in Table 6.1 have not necessarily been used in studies of ICLARM's village-farming trials reported in the literature. Hart *et al.* (1998) assume *T. crocea* (3.5 cm and 5 cm), *T. derasa* (7.5 cm and 15 cm) and *T. maxima* (3.5 cm and 5 cm) seed sell for US\$0.50 per seed. Bell *et al.* (1997b) assume *T. gigas* (3.5 cm) seed sell for US\$0.50 per seed. These prices were based on estimates of the production cost of *T. gigas* seed made by Hambrey and Gervis (1993) and Tisdell *et al.* (1993a, 1993b) for 500,000 seed per year facilities. These prices convert to about SBD\$2 per seed,

depending on the exchange rate, which is higher than the corresponding prices in Table 6.1. Foyle *et al.* (1997) assume *T. squamosa* (2.4 cm) seed sell for US\$0.33 per seed. This converts to about SBD\$1.32, depending on the exchange rate, which is close to the price for this seed in Table 6.1.

Gervis *et al.* (1995) claim that ICLARM charge farmers for the delivery of clam seed to their farms. Hambrey and Gervis (1993) indicate that for farms other than those in the immediate vicinity of the ICLARM CAC, the delivery charge could be anywhere in the range SBD\$0.01-0.10 per seed, depending on the location of the farm and the size of the delivery. This cost could not be substantiated and was therefore disregarded in this study. Discussions with ICLARM staff and clam farmers suggested that seed is delivered to the farms at no charge during monthly site visits. This represents another implicit subsidy. Such an arrangement is unlikely to be continued once the emerging industry has matured and ICLARM has transferred its responsibilities to a private hatchery.

Table 6.1 was used to estimate step-price functions for *T. crocea* and *T. derasa* seed for the model (see Figure 6.1). Shell lengths were converted to wet weights (tissue plus shell,  $w$ ) by manipulating the allometric relationships described in Chapter 5 (parameter values for these relationships are presented in Chapter 7).



**Figure 6.1. Step-price functions for clam seed for both species**

In the base-model runs, the shell lengths of the *T. crocea* and *T. derasa* seed are assumed to be 2.01 cm and 2.75 cm respectively. These were the mean shell lengths of the seed of these species in the ICLARM village-farming trials described in Section 6.3.1, for which data was used for calibration of the growth model. These shell lengths convert to wet weights (tissue plus shell) of  $1.313 \times 10^{-3}$  kg and  $1.245 \times 10^{-3}$  kg respectively, and were taken for the clam-seed sizes ( $w_0$ ) of the species (see Table 6.13). The prices of these seed are SBD\$1.15 for *T. crocea* and SBD\$0.90 for *T. derasa*. In the base model, only one cage of clams is planted with 200 seed, at the start of the planning horizon; this is  $N_0$  for both species in Table 6.13. This is consistent with the number of clam seeds planted per cage in the ICLARM farming trials described in Section 6.3.1, and other ICLARM trials not described here (which range from 200-250 seed clams/cage). Both  $w_0$  and  $N_0$  are decision variables in the model, but they are maintained at their base values throughout this study.

## 6.2.2 Labour

Estimating the input and cost of labour and the relationship between labour and the decision variables in the bioeconomic model was not trivial, because of the variety of tasks required. Over a production cycle, labour is required for activities such as planting, cleaning, thinning and harvesting. Planting consists of putting clam seed into cages and affixing the cages to trestles at a grow-out site on a fringing reef. Cleaning involves keeping the cages free of algal build-up (which would reduce light and inhibit water flow) and predators. Thinning means reducing the number of clams per cage (increasing the number of cages) as the clams grow in order to avoid the negative effects of crowding. Harvesting entails collecting clams of marketable size from the cages and preparing them for transport and sale. These activities are discussed in more detail in Chapter 3 and later in this section.

ICLARM recommends labour input would need to be about three half-days per week to achieve good clam growth and survival on an established farm of 70 cages at a typical farm site (see Bell *et al.*, 1997b; Foyle *et al.*, 1997; Gervis *et al.*, 1995; Govan, 1993). This would total 9-12 hours, regardless of the species being farmed, and would

cover all necessary planting, cleaning, thinning and harvesting, as well as any cage and trestle construction and maintenance required (Tafea and Lasi, 1997, pers. comm.). The intensity with which these activities would be undertaken each week would vary over the production cycle. Less than 9-12 hours each week would be required if environmental conditions at a farm site were particularly suited to farming clams, or if farmers were to purchase their capital equipment rather than construct and maintain it themselves. This amount of labour would be spread across several villagers on farms tended by groups. For a farm tended by a single villager, 12 hours per week would likely be the maximum labour input that could be expected given their commitment to community, subsistence and other income-earning activities (Bell, 1997, pers. comm.).

ICLARM recommends that cleaning and thinning be routinely undertaken each week, planting and harvesting can be undertaken less frequently as the need arises. Cleaning is particularly time consuming when the clams are small and prone to predation, it becomes less intensive once the clams are large and their cages can be left uncovered providing access for grazing fish. Thinning becomes increasingly intensive as the clams grow and more cages are required on the farm. Thinning incorporates grading, where clams of a similar size are placed in the same cage, since clams of a similar size grow better together. ICLARM recommends that every cage on the farm be thinned every 6-12 months (Bell and Lane, 1997, pers. comm.). When a particular cage needs thinning will depend on the growth and mortality of the clams in the cage; it should proceed when cage space becomes limiting when the clam mantles are fully extended. Some ICLARM staff and village farmers believe that all the cages on a farm should be removed from the water every 6-12 months and cleaned, thinned and graded on the shore (eg. Lane, 1997, pers. comm.). Although this practice may improve clam survival, it has been shown to reduce growth (see Bell *et al.*, 1997b). It would also be very impractical for an established farm with 70 cages on the reef.

To implement the model, the labour input had to be estimated for each activity (ie. planting, cleaning, thinning and harvesting) on a per cage or per clam basis. These estimates could not be easily devolved from the aggregate data described above for an established farm, and were therefore estimated independently. These estimates are presented in Table 6.2. Labour input for cage and trestle construction and

maintenance is not included in Table 6.2. Clam farmers can purchase their capital equipment rather than construct or maintain it themselves, hence labour to build and repair cages and trestles is treated as a capital expense and is described in Section 6.2.3.

**Table 6.2. Labour input for giant-clam production**

Activity ( <i>i</i> )	Labour input ( $L_i$ )	Units
Planting	0.5	hrs/cage
Cleaning	$0.0036H-0.0036$	hrs/day/cage
Thinning	0.025	hrs/clam
Harvesting	0.05	hrs/clam

Labour input for planting, thinning and harvesting was fairly straightforward to estimate. Planting was estimated to take approximately 30 minutes per cage. This would allow sufficient time to plant 200 clam seeds in a cage, swim the cage to the reef and affix the cage to a trestle. Thinning was estimated to take approximately 1.5 minutes per clam. In this time, a farmer could take a clam from a crowded cage, grade it according to its size and place it in a less crowded cage with other clams of a similar size. This time allowance would also cover the time required to swim any additional cages needed from the village to the farm and affix those cages to trestles. Harvesting was estimated to take approximately 3 minutes per clam. This would be enough time to identify the clams of marketable size, swim them to shore, clean them of any visible algae and pack them into a portable cooler ready for transport and sale. Some ICLARM staff and village farmers considered certain species were more difficult to harvest given their burrowing habit or the presence of breakable scutes on their shell, and would therefore take more time to harvest if they were not to be damaged (eg. Tafea and Lasi, 1997, pers. comm.). However this complication was disregarded in this study because other experts did not agree with this view (Bell, 1997, pers. comm.).

Labour input for cleaning was more complicated to estimate given there is a relationship between the time spent cleaning and the cleanliness of the cages. For farming trials with several species, including those for *T. crocea* and *T. derasa* described in Section 6.3.1, ICLARM collected data on the level of “husbandry”.

Husbandry is a subjective measure of cage cleanliness and is measured on a scale from 1 (non-existent) to 5 (excellent) (see Hart *et al.*, 1998). For this study, it was assumed that labour input and husbandry are linearly related, and that for an established farm of 70 cages at a typical grow-out site, excellent husbandry takes 6 hours per week and non-existent husbandry involves no labour input at all. The effect of husbandry on clam growth was explained in Chapter 5 (see equation (5.14)-(5.15)).

In the model, the level of husbandry ( $H$ ) and the frequency of thinning ( $TF$ ) are decision variables, and their role is explained in Chapter 8.

Estimating the cost of labour was not a trivial matter. Village farmers do not generally participate in the formal labour market so the value of their labour is not easy to measure. Villagers generally engage in subsistence gardening, poultry and livestock production (mainly chickens and pigs) and fishing to provide food for their household; any surplus vegetables, animals or fish may be sold at local markets to provide a small amount of cash income. Villagers may also undertake some small-scale opportunistic commercial activities for local markets, exporters and developers (such as Ross Mining near Honiara, Guadalcanal and the Solomon Taiyo Fish Cannery at Noro, Western Province). This may include growing copra, reef fishing, farming corals, collecting trochus and beche-de-mer, constructing sago palm roofing, keeping bees, cutting timber and providing water transport. Some villagers may get a job in logging, mining, fish processing, plantations (copra, cocoa or coffee) or tourism, and receive a wage.

The most likely alternative commercial activity for villagers engaged in clam farming is copra production from their own coconut plantation. The net return to labour for copra production was estimated and used as the opportunity cost of labour. The lowest and highest net returns estimated for this activity are presented in Table 6.3.

To produce copra, villagers collect coconuts from palms, husk and split them into halves to reveal the flesh inside, dry the half-shells in the sun or a wood-fuelled air-drier for several days, and hand-extract the cured copra from the half-shells. If they weren't farming clams, villagers would probably produce copra 2-3 times per year to satisfy cash-flow requirements (eg. to pay for school fees). On each occasion, this



would involve 2-4 men working full-time for about three weeks to produce 6-8 bags of copra each containing 60-80 kg (ie. totalling 360-640 kg of copra). The price received for the copra would be either SBD\$0.48 per kg or SBD\$0.62 per kg depending on the buying centre at which it was sold (eg. Gizo, Western Province or Marau, Gaudalcanal, respectively). The production costs incurred would include bags (SBD\$4 per bag), hire of an air-drier (SBD\$3-4 per bag), firewood (SBD\$5-7.50 per bag) and transport from the village to the buying centre (SBD\$6 per bag). If the half-shells were sun-dried, production costs would not be incurred for the hire of an air-drier or the firewood to fuel it. Based on this information, the net return to labour would range between SBD\$0.10-1.51 per hr (Table 6.3). This compares with estimates for full-time labour employed on commercial plantations of US\$0.25 per hr (about SBD\$1 per hr depending on the exchange rate) reported by Bell *et al.* (1997b) and SBD\$1-1.50 per hr understood to be the going rate by other ICLARM staff. The opportunity cost of labour was therefore estimated to be SBD\$1.50 per hr and was taken as the wage rate,  $P_L$ , for this study (see Table 6.13).

**Table 6.3. Estimated net return to labour for copra production from a village plantation**

Copra production	Estimated return to labour		Units
	Lowest	Highest	
<b>Labour</b>			
2-4 villagers full-time (35 hrs/week) for 3 weeks	420	210	hrs
<b>Production</b>			
6-8 bags @ 60-80 kg/bag	360	640	kg
<b>Total revenue</b>			
Copra sold for SBD\$0.48/kg or SBD\$0.62/kg	172.80	396.80	SBD\$
<b>Total costs</b>			
Bags (SBD\$4/bag)	24	32	SBD\$
Air-drier hire (SBD\$3-4/bag)	24	nil <sup>a</sup>	SBD\$
Firewood (SBD\$5-7.50/bag)	45	nil <sup>a</sup>	SBD\$
Transport (SBD\$6/bag)	36	48	SBD\$
Total	129	80	SBD\$
<b>Profit</b>	43.80	316.80	SBD\$
<b>Net return to labour (Profit/Labour)</b>	0.10	1.51	SBD\$/hr

<sup>a</sup> Costs for air-drier hire and firewood would not be incurred if the copra were sun-dried.

### 6.2.3 Capital

Capital inputs for clam farming include variable inputs and fixed inputs. Variable inputs generally comprise cages and trestles. Cages are typically 77cm long, 65cm wide and 13.3cm high (ie. 5005 cm<sup>2</sup>) and made from wire mesh. Trestles are typically 2.8m long, 0.8m wide and 0.6m high (ie. 2.24 m<sup>2</sup>), and constructed from steel rods, they are designed to support up to 4 cages above the reef floor. Tafea (1993) and Lane (1995) describe their design and construction. Farmers may also use enclosures, where cages are placed on the reef floor and covered by a protective mesh frame. Depending on the design of the enclosure, 2-4 cages can be protected in this way. Enclosures were not in general use when the author was on field research in Solomon Islands in 1997, although ICLARM was experimenting with them for *T. derasa* planted directly on the sea floor (ie. not in cages). *T. derasa* had consistently proven the most robust species in ICLARM farming trials (Hart *et al.*, 1998; Bell *et al.*, 1997a) and it was hoped good growth and survival could be achieved with this planting practice, significantly reducing the capital required to farm this species. Other species can not be planted directly on the reef floor because they are not sufficiently robust. It was therefore decided to disregard enclosures as variable capital inputs in this study. Fixed capital inputs include goggles, mask, snorkel, scrubbing brush, harvest knife, pliers, wire cutters, cement trowel, callipers and a portable cooler. These inputs are required irrespective of the scale of clam production and have no influence on optimal model solutions.

ICLARM considers that the maximum manageable farm size is 70 cages (Gervis *et al.*, 1995). This estimate is based on the assumption that villagers would have sufficient time after undertaking customary village activities to spend on a farm this size and achieve good clam growth and survival (see Section 6.2.2). This number of cages could also be appropriately located on the reef and still be sufficiently near a farmer's village for easy access and security (see Covan, 1993). Although 70 cages would only take up 35 m<sup>2</sup> of actual reef space, they would be spread across a much larger area. This is because cages should not be placed above live coral, because it dies due to the reduction in light, so cages should be placed in the coral rubble gaps

between the live coral. Observations from farm visits were that only a few farms approached 70 cages.

The amount of capital required on the farm at any one time depends on the extent of planting, thinning and harvesting. It does not differ with the species being farmed although some species may grow larger and more rapidly than others and require more thinning. Mortality of the clams in the cages may also affect the need for thinning and thereby farm capital. *T. derasa* has very good growth and survival, suggesting that this species may need to be thinned most frequently (see Hart *et al.*, 1998).

ICLARM believes that if giant-clam farming becomes an established industry in Solomon Islands, farmers could expect to receive about 3000 seed clams per year in up to three plantings (Bell, 1997, pers. comm.). This would require 15 cages (assuming a density of 200 seed clams per cage) and 4 trestles (since each trestle can support up to 4 cages) per year. The number of cages and trestles required on the farm would increase with thinning, and decrease with harvesting. New cages and trestles might not need to be constructed or purchased to meet increasing demand, since capital inputs can be maintained for more than one production cycle. The steel rod trestles can be maintained for up to 10 years, while the wire mesh cages deteriorate much more rapidly and can only be maintained for about two years (Tafea, 1997, pers. comm.). The reuse potential of cages and trestles was ignored in this study however.

In the base-model runs, one cage of clams is planted at the start of the planning horizon, with 200 seed clams ( $N_0$  in Table 6.13). Thinning is undertaken at specific weekly intervals (such as every 26 or 52 weeks) and reduces the number of clams per cage (by increasing the number of cages) until the number of cages on the farm reaches a maximum of 16. This upper limit would accommodate the seed clams at the end of their production cycle if they were all to survive. If thinning were to proceed to 16 cages in this zero-mortality case, the number of clams per cage would halve (from 200 to 100, 50, 25 and then 12.5 (allowing for non-integers)) and the number of cages would double (from one to 2, 4, 8 and finally 16). The number of clams per cage after each thinning in this zero-mortality case is regarded as the “target number” for each

thinning, and is used to determine the extent to which thinning is undertaken when mortality is positive. If clams die during the production cycle and there are fewer clams per cage at thinning time than the target number, thinning does not proceed. If there are more clams per cage than the target number, thinning proceeds until there are sufficient cages on the farm to make the number of clams per cage equal to the target number. Hence, thinning may not halve the number of clams per cage or double the number of cages.

The cost of capital ( $P_K$ ) was calculated for a “standard” cage comprising one cage plus one quarter of a trestle. To calculate  $P_K$ , estimates were required for the cost of materials and the labour cost of construction for cages and trestles. These costs are itemised in Table 6.4. The cost of materials was estimated by Tafea (1997, pers. comm.) to be SBD\$29.70 per cage and SBD\$44.20 per trestle. This is the financial cost of the materials which are provided to the village farmers on credit, rather than their total resource cost which is incurred by ICLARM. As for clam seed (see Section 6.2.1), village farmers are not charged the interest cost associated with this advance, which represents an implicit subsidy. The labour cost of construction was estimated by the author to be SBD\$2.25 per cage and SBD\$1.50 per trestle, assuming construction takes 1.5 hrs per cage and 1 hr per trestle (Bell and Lane, 1997, pers. comm.), and village labour is worth SBD\$1.50 per hr. The total cost per cage and per trestle was therefore estimated to be SBD\$31.95 and SBD\$45.70 respectively (see Table 6.4), and the corresponding cost of a standard unit ( $P_K$ ) was estimated to be SBD\$43.38 (see Table 6.13).

$P_K$  may be overestimated because the reuse potential of cages and trestles is ignored. An alternative approach would have been to base the cost of capital on an annuity that accounts for the expected life span of the cage and trestle components. The former approach was taken due to the benefits of simpler modelling.  $P_K$  compares with US\$8.50 and US\$11 (which average about SBD\$39 depending on the exchange rate) assumed for cage construction by Bell *et al.* (1997b) and Hart *et al.* (1998).

In the model, the area of a standard cage ( $CA$ ) was taken to be 5005 cm<sup>2</sup>.

**Table 6.4. Cost of cages and trestles**

Capital input	Cost (SBD\$)
Cage	
Wire mesh (1.92 m)	24.00
Cement (2 kg)	2.70
Tie wire (1.5 m)	3.00
Construction (1.5 hrs)	2.25
Total	31.95
Trestle	
Steel rods (2)	42.20
Tie wire (1m)	2.00
Construction (1 hr)	1.50
Total	45.70

#### **6.2.4 Marketing Services**

Marketing services include internal transport and airfreight of harvested clams from the farm to the exporter in Honiara. The village farmer covers the cost of marketing services. International transport and airfreight are not included because the exporter meets these costs. Bell *et al.* (1997a) discuss transport and airfreight considerations for *T. derasa* for export to the live seafood market. Similar considerations apply for aquarium species.

Most farmers transport their clams by boat from their farm to a regional airport where an intermediary arranges their airfreight with Solomon Airlines to Henderson International Airport on Honiara's outskirts. The clams are then collected by ICLARM staff and delivered to the exporter in town. These services are provided free of charge and represent a further implicit subsidy. The intermediaries are Paruru Aquaculture in Marau, Solomon Islands Department of Fisheries and Agriculture on the Russell Islands, and ICLARM's Nusa Tupe Field Station in the Western Province. Some farmers on the Florida Islands are sufficiently close to the ICLARM CAC to transport their clams themselves by boat and avoid airfreight.

Transporting clams by boat can be a time-consuming activity for village farmers. It can take them from 30 minutes up to 6 hours for a return trip from their farm to the regional airport depending on the propulsion of their boat and the distance they need

to travel (Tafea and Lasi, 1997, pers. comm.). If their boat is engine-powered, they also require fuel. Rather than incur these expenses village farmers can have their clams collected by ICLARM staff for a flat fee of SBD\$10/harvest (Tafea and Lasi, 1997, pers. comm.). This fee may not reflect the total resource cost of this service. It is used as a proxy for the fixed cost of boat transport in this study. Bell *et al.* (1997b) indicate that if farmers do not deliver their clams to the regional airport themselves, they may have to rely on another party to make the delivery at a cost of 10-20 percent of the value of the clams. If this were the case, boat transport would be a variable cost and would affect optimal model solutions.

Internal airfreight can be particularly costly. In 1997, farmers most distant from Honiara were paying SBD\$2.80-3.60 per kg depending on the quantity being airfreighted. Most farmers were paying SBD\$0.95 per kg (Tafea, 1997, pers. comm.) and this was taken as the price of marketing services,  $P_M$  (see Table 6.13). This compares with estimates for internal airfreight of US\$0.72 per kg and US\$0.95 per kg charged to the farmers in the respective studies by Bell *et al.* (1997b) and Hart *et al.* (1998) (which convert to SBD\$2.88 per kg and SBD\$3.80 per kg respectively, at the base exchange rate). Bell *et al.* (1997a) suggest airfreight on domestic flights is too limited and too costly to transport commercial quantities of *T. derasa* for the live seafood market and expect the industry in Solomon Islands to develop in places within 6-10 hours boat ride of the exporter. Transport costs may significantly affect the viability of farms in distant areas, something that is not picked up in this study, given the assumption  $P_M$  is a factor of harvest size.

Bell *et al.* (1997b) and Hart *et al.* (1998) also charged clam farmers with a handling fee of US\$0.10 per clam and US\$0.12 per clam respectively. According to Bell (1997, pers. comm.), this fee covers the costs incurred by ICLARM of facilitating the sale of clams for the village farmers. However, in retrospect, Bell thought this fee should be charged to the exporter rather than the village farmer. A handling fee was therefore not included in the price of marketing services in this study.

## 6.2.5 Marketable Clams

Village farmers sell their marketable clams to ICLARM who facilitates their sale with local exporters in Honiara. In 1997, the only active market for giant clams was the aquarium market. ICLARM had supplied this market in the United States and Europe with an average of two shipments per week since 1994 through Solomon Islands Marine Exports. There was no established market for seafood clams, although ICLARM was engaged in trial shipments of both live and dead clams to Asia and Japan. Live clams are exported through Solomon Islands Marine Exports and dead clams through Island Seafoods Ltd (Battaglione, 1997, pers. comm.).

**Table 6.5. Prices for marketable aquarium clams received by village farmers**

Shell length (cm)	<i>T. crocea</i> (US\$)	<i>T. derasa</i> (US\$)	<i>T. gigas</i> (US\$)	<i>T. maxima</i> (US\$)	<i>T. squamosa</i> (US\$)	<i>H. hippopus</i> (US\$)
2.54	1.20	0.54	0.68	1.02	1.02	0.54
4.00	2.27	0.83	0.99	2.00	1.65	0.74
5.00	3.18	1.24	1.65	2.70	2.23	1.11
8.00	4.46	1.24	2.48	3.80	3.14	1.65
10.00	-	1.57	3.38	5.40	4.46	2.31
12.50	-	1.90	4.37	7.20	5.94	3.05
15.00	-	2.31	3.39	-	-	2.31
17.50	-	2.73	4.27	-	-	3.06
20.00	-	-	5.72	-	-	-
22.50	-	-	7.22	-	-	-
25.00	-	-	8.27	-	-	-
27.50	-	-	9.24	-	-	-
30.00	-	-	10.56	-	-	-

Prices received by village farmers for aquarium clams of all species farmed in Solomon Islands are reported in Table 6.5. These prices were current as at 5 January 1998. The minimum shell lengths commanding each price are reported. Clams shorter than 2.54 cm are not saleable, this is also the case for clams in the shell length categories for which no price is reported. To cover the costs of its facilitation role, the prices paid by ICLARM to the village farmers are 17.5 percent lower than the prices they receive from the exporters (Gervis *et al.*, 1995).

Similar prices for aquarium clams have been reported in other studies of ICLARM's village-farming trials. Bell *et al.* (1997b) assumed US\$2.00 and US\$3.00 per clam for 5-7.5 cm and 7.5-10 cm *T. gigas* respectively. Foyle *et al.* (1997) assumed US\$1.86 per clam for 5 cm *T. squamosa*. Hart *et al.* (1998) assumed US\$2.27 and US\$3.18 per clam for 3.5 cm and 5 cm *T. crocea* respectively, US\$1.24 and US\$2.31 for 7.5 cm and 15 cm *T. derasa* respectively, and US\$1.65 and US\$2.23 for 3.5 cm and 5 cm *T. maxima* respectively. Bell *et al.* (1997b) suggest that a 60 percent increase in the farm price of marketable clams is possible if farmers can sell direct to the wholesaler. This approximates the sum of the marketing margins charged by ICLARM (17.5 percent) and the exporter (40 percent) (Bell, 1997, pers. comm.).

Prices for seafood clams are uncertain due to the emerging nature of the live and dead seafood markets. In 1997, ICLARM had undertaken a few trial shipments of live clams to Beijing, Hong Kong and Taiwan, and a single trial shipment of dead clams to Okinawa, Japan (Battaglione, 1997, pers. comm.). In each case, the shipments comprised 15-cm *T. derasa* and the village farmers were paid the aquarium price (Tafea, 1997, pers. comm.). This price reflected a policy decision by ICLARM rather than market reality. Bell *et al.* (1997a) discuss the suitability of *T. derasa* for the live seafood market.

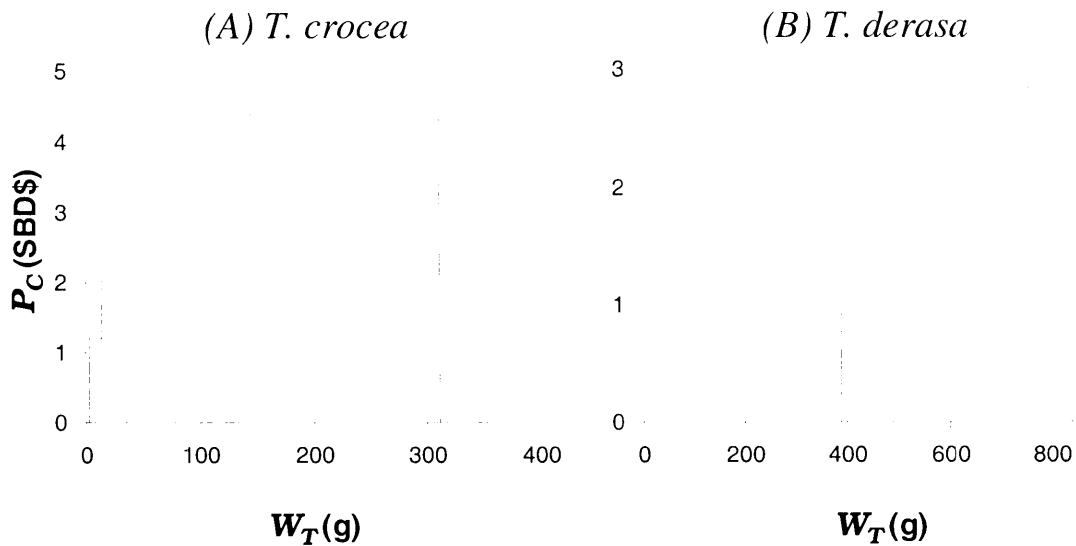
The prices reported in Table 6.5 were used to estimate price functions for marketable clams for *T. crocea* and *T. derasa* (Figure 6.2). Shell lengths were converted to wet weights (tissue plus shell,  $w_T$ ) by manipulating the allometric relationships described in Chapter 5 (parameters values for these relationships are presented in Chapter 7).

It is assumed that *T. derasa* less than 15 cm in shell length are not saleable (see Bell *et al.*, 1997a). The price function for *T. derasa* is a linear approximation of the data for clams greater than 15 cm in shell length ( $SL$ ), as follows:

$$P_c = \begin{cases} 0 & \text{if } SL < 15\text{cm} \\ -0.21 + \text{grad}P \cdot SL & \text{if } SL \geq 15\text{cm} \end{cases}$$



$gradP$  is the slope of the function. This function was estimated because there is so much uncertainty about the prices that will emerge for seafood clams. An alternative approach would have been to base this price function on the prices of related products in similar markets.

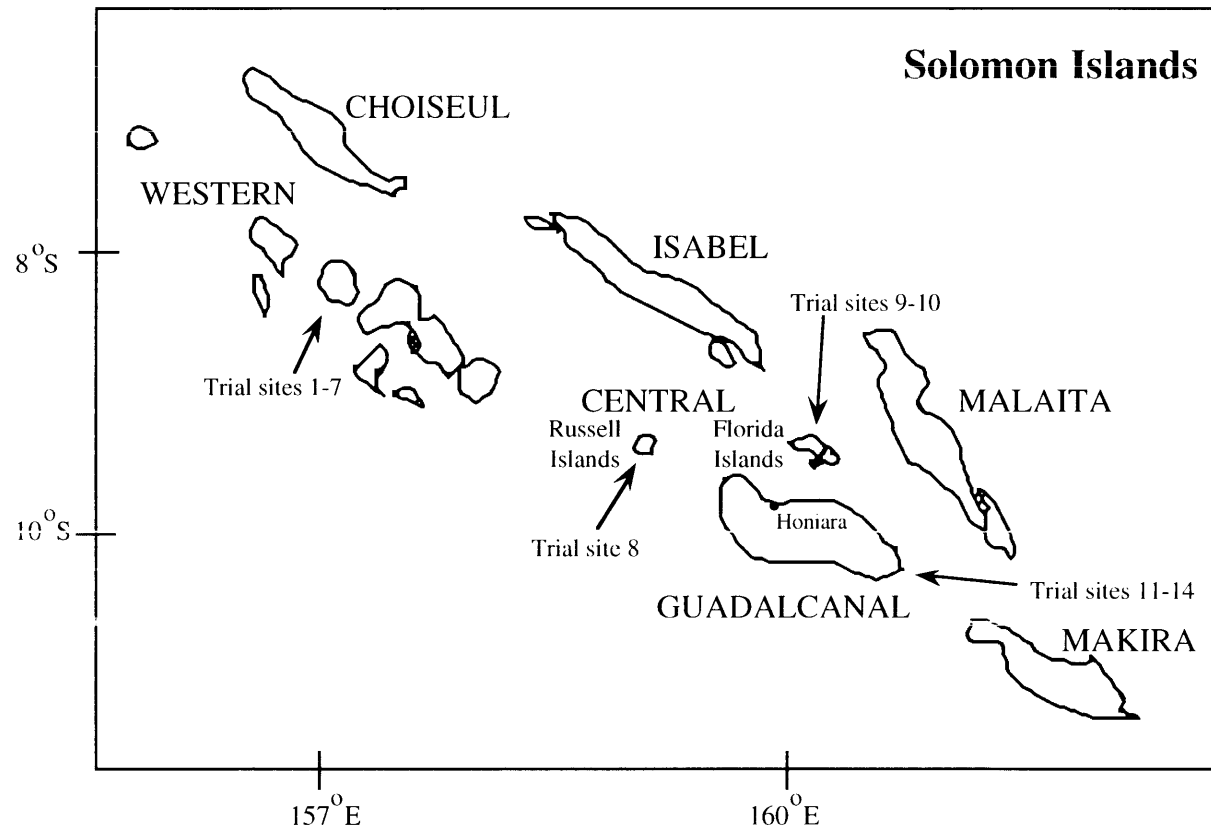


**Figure 6.2. Price functions for marketable clams for both species**

In the model, the prices received by the farmers for their clams are converted from US\$ to SBD\$ by dividing the US\$ price by the exchange rate,  $X_r$  (equation (5.11)). The value for  $X_r$  in this study is 0.25 US\$/SBD\$.

### 6.3 Biological Data

Biological variables affect giant-clam farm profitability through clam yield. ICLARM collected biological data for *T. crocea* and *T. derasa* from farming trials at a variety of village sites in Solomon Islands during the mid-1990s. The trials are described below. The biological data used for this study is also described; it includes growth, survival and environmental data.



**Figure 6.3. Map of ICLARM's village-farming trail sites**

### 6.3.1 Village-farming trials

ICLARM established a series of farming trials for *T. crocea* and *T. derasa* at 14 village farms spread across Solomon Islands as part of an ACIAR-funded project, “Large-scale village grow-out trials for giant clams”. Hart *et al.* (1998, 1999) report some of the results of these trials.

**Table 6.6. Locations of ICLARM’s village-farming trial sites**

Trial site	Location
1	Vella Lavella, Western Province
2	Varu Island, Western Province
3	Nusa Tupe, Western Province
4	Vona Vona, Western Province
5	Vona Vona, Western Province
6	Munda, Western Province
7	Munda, Western Province
8	Niu Tanggini, Russell Islands, Central Province
9	Buena Vista, Florida Islands, Central Province
10	Buena Vista, Florida Islands, Central Province
11	Marau, Guadalcanal
12	Marau, Guadalcanal
13	Marau, Guadalcanal
14	Marau, Guadalcanal

The locations of the trial sites are provided in Table 6.6 and Figure 6.3. The *T. crocea* trials ran from March 1995 to January 1997 (22 months) at sites 1 to 12. At each *T. crocea* trial site, four cages were planted with 200 seed clams per cage. The *T. derasa* trials ran from December 1994 to December 1996 at sites 1 to 14. At each *T. derasa* trial site, eight cages were planted with 200 seed clams per cage. In these trials, four cages were first planted in December 1994 and monitored for the entire two-year trial period, whereas the remaining four cages were planted in January 1995 and only monitored for one year. ICLARM collected growth, survival and environmental data for all the trial cages. For *T. crocea* there were 48 cages from which data was collected (12 sites with 4 cages per site). All the clams in one cage at site 7 (Munda, Western Province) died in the four months following planting, so no growth data could be collected for this cage. It was therefore omitted from the analysis, leaving 47

cages of data. For *T. derasa* there were 112 cages from which data was collected (14 sites times 8 cages per site). All these cages were included in the analysis.

### 6.3.2 Growth

ICLARM measured the growth of the clams at regular intervals (3-5 monthly) throughout the duration of the farming trials. On each occasion, the shell length of 30 to 50 clams was measured per cage and the mean and standard deviation calculated. This provided time-series growth data for each cage, which was used for calibration of the growth model, as described in Chapter 7.

Growth data for *T. crocea* comprises a trace of six observations per cage, while growth data for *T. derasa* comprises traces of either four or eight observations per cage depending on when the cages were planted. For illustration, mean growth data is presented for a cage of *T. crocea* and a cage of *T. derasa* in Tables 6.7 and 6.8 respectively.

**Table 6.7. Growth data for a *T. crocea* cage farmed at Trial site 3**

Date	Number of days from planting	Mean shell length (cm)
23 March 1995	0	2.11
16 August 1995	146	2.65
25 January 1996	308	3.54
21 May 1996	425	4.21
23 August 1996	519	4.65
21 January 1997	670	5.64

The mean shell lengths of the seed used in the trials were 2.01 cm and 2.75 cm for *T. crocea* and *T. derasa* respectively. These shell lengths were converted to wet weights (tissue plus shell) of  $1.313 \times 10^{-3}$  kg and  $1.245 \times 10^{-3}$  kg respectively, based on the allometric relationships described in Chapter 5, and were taken for the clam-seed sizes ( $w_0$ ) of the species in base-model runs.

**Table 6.8. Growth data for a *T. derasa* cage farmed at Trial site 4**

Date	Number of days from planting	Mean shell length (cm)
15 December 1994	0	2.87
19 April 1995	125	6.27
18 August 1995	246	8.87
18 December 1995	368	10.34
22 March 1996	463	11.41
26 June 1996	559	12.56
27 September 1996	652	13.54
20 December 1996	736	14.52

*T. crocea* grew an average of 3.03 cm to 5.04 cm in shell length in the 22 months of the trial. The seed in the December 1994 planting of *T. derasa* grew an average of 11.99 cm (from 2.98 cm to 14.97 cm) in two years, while the seed in the January 1995 planting grew an average of 7.47 cm (from 2.53 cm to 10.00 cm) in one year. The growth rates of both species differed significantly among trial sites (Hart *et al.*, 1998).

### 6.3.3 Survival

ICLARM monitored the survival of the clams at regular intervals throughout the duration of the trials by counting the number of live clams in each cage. For the first year, monitoring was undertaken on a monthly basis or until the survival of the clams stabilised and then less frequently thereafter. The survival of *T. crocea* was monitored on 17 occasions, while the survival of the December 1994 and January 1995 plantings of *T. derasa* were monitored on 15 and 9 occasions respectively. This provided time-series survival data for the number of clams per cage, which was used for calibration of the growth model (described in Chapter 7). Survival data is presented for a cage of *T. crocea* and a cage of *T. derasa* in Tables 6.9 and 6.10 respectively.

To prevent the negative effects of density on growth, the cages were thinned during grow-out (Hart *et al.*, 1998). The *T. crocea* cages were thinned on one occasion after 17 months (in August 1996) to 50 clams per cage. This is clearly documented in Table 6.9 where there are pre- and post-thinning entries for the number of clams per cage for August 1996. The survival of the clams removed from the trial cages was not

monitored following thinning. The *T. derasa* cages were thinned on three occasions at 4, 8 and 12 months. On each occasion, half the clams were kept in the cages and the other half were given to the village farmers for commercial production. Unfortunately, thinning is not well documented in the survival data collected for *T. derasa*, making it sometimes impossible to differentiate between the number of clams removed from the cage and those that have died.

**Table 6.9. Survival data for a *T. crocea* cage farmed at Trial site 3**

Date	Number of days from planting	Number of clams in cage
23 March 1995	0	200
19 April 1995	27	179
19 May 1995	57	172
20 June 1995	89	120
18 July 1995	117	115
16 August 1995	146	113
19 September 1995	180	110
26 October 1995	217	109
15 November 1995	237	107
12 December 1995	264	105
25 January 1996	308	97
22 February 1996	336	93
22 March 1996	365	91
21 May 1996	425	85
23 August 1996	519	84
23 August 1996	519	50
17 October 1996	574	39
21 January 1997	670	36

It was attempted to use the data collected from ICLARM to estimate a survival function based on regression models of environmental variables and husbandry but no significant relationships (in a statistical sense) were found. Hart *et al.* (1998) also found that regression models for survival were a poor fit to the available data. For this study, the problem was compounded by the confounding effect of thinning. It was therefore decided to use a simple decay function to describe survival for each species as described in equation (5.40).

**Table 6.10. Survival data for a *T. derasa* cage farmed at Trial site 4**

Date	Number of days from planting	Number of clams in cage
15 December 1994	0	200
25 January 1995	41	200
22 February 1995	69	218
23 March 1995	98	213
19 April 1995	125	218
21 June 1995	188	105
18 August 1995	246	106
24 October 1995	313	49
18 December 1995	368	49
26 January 1996	407	49
22 March 1996	463	25
24 May 1996	526	25
26 June 1996	559	25
27 September 1996	652	25
20 December 1996	736	25

Hart *et al.* (1998) report mean survival rates for *T. crocea* of 38.9 percent after 17 months, dropping to 28 percent after 22 months (this decline coincided with thinning). In the same study, the mean survival of *T. derasa* was 92.2 percent after 2 years of grow-out, regardless of thinning frequency. There were significant differences in survival of *T. crocea* between trial sites; this did not apply for *T. derasa* (Hart *et al.*, 1998). Based on this information, the mean daily mortality rate ( $\mu$ ) was estimated to be 0.0019 clams/cage/day and 0.00011 clams/cage/day for *T. crocea* and *T. derasa* respectively.

#### **6.3.4 Culture Environment**

ICLARM monitored the culture environment at each of the trail sites on the same occasions survival was measured. Data was collected on several environmental variables and the level of husbandry. At the time the trials commenced, the depths at which the cages were secured to trestles were also recorded. For this study, these depths were assumed to apply for the duration of the trials, abstracting from the complications caused by tidal changes. This provided time-series data for the culture environment for each cage, which was used for calibration of the growth model.

Environmental and husbandry data is presented for a cage of *T. crocea* and a cage of *T. derasa* in Tables 6.11 and 6.12 respectively.

**Table 6.11. Environmental and husbandry data for a *T. crocea* cage farmed at Trial site 3, at a depth of 2.68 m**

Date	Number of days from planting	Day number of the year	Water temperature (°C)	Secchi disk visibility (m)	Husbandry
23 March 1995	0	82	31.0	36.9	5
19 April 1995	27	109	31.0	19.0	3
19 May 1995	57	139	30.5	20.0	4
20 June 1995	89	171	27.9	19.0	4
18 July 1995	117	199	29.2	18.0	2
16 August 1995	146	228	29.8	21.0	4
19 September 1995	180	262	30.0	25.0	4
26 October 1995	217	299	31.2	23.0	4
15 November 1995	237	319	30.7	20.0	4
12 December 1995	264	346	30.7	25.0	4
25 January 1996	308	390	31.7	16.0	4
22 February 1996	336	418	31.7	16.0	4
22 March 1996	365	447	30.7	24.0	4
21 May 1996	425	507	30.2	13.0	4
23 August 1996	519	601	30.6	12.0	4
17 October 1996	574	656	30.7	18.0	3
21 January 1997	670	752	30.2	13.0	4

The environmental variables in the biophysical model are water temperature, irradiance, depth, Secchi disk visibility and the particulate organic carbon content of the water. Recall that in the model, water temperature ( $Temp$ ) is estimated by a sine function (equation (5.41)) and irradiance ( $I_{thr}$ ) is estimated by a cosine function (equation (5.44)). In these functions, the latitude ( $Lat$ ) for Solomon Islands is  $10^\circ$ , and the autumn equinox ( $Z$ ) is 101 days after January 1.

In base-model runs, the depth ( $D$ , equation (5.46)) at which the cages are farmed is assumed to be constant at 1.29 m; this is the mean of cage depth for the pooled *T. crocea* and *T. derasa* trials, which had means of 1.21 m and 1.37 m respectively. Secchi disk visibility ( $V_{SD}$ , equation (5.47)) is assumed to be constant at 14.18 m; this is the mean for the pooled *T. crocea* and *T. derasa* trials, which had means of 14.22 m and 14.14 m respectively.



**Table 6.12. Environmental and husbandry data for a *T. derasa* cage farmed at Trial site 4, at a depth of 0.85 m**

Date	Number of days from planting	Day number of the year	Water temperature (°C)	Secchi disk visibility (m)	Husbandry
15 December 1994	0	349	30.0	26	5
25 January 1995	41	390	30.5	13	4
22 February 1995	69	418	30.5	14	3
23 March 1995	98	447	30.5	15	4
19 April 1995	125	474	31.4	7	4
21 June 1995	188	537	29.4	10	4
18 August 1995	246	595	29.2	11	4
24 October 1995	313	662	31.7	9	3
18 December 1995	368	717	31.7	14	3
26 January 1996	407	756	32.2	7	4
22 March 1996	463	812	32.2	8	4
24 May 1996	526	875	30.4	8	3
26 June 1996	559	908	31.0	5	4
27 September 1996	652	1001	31.5	10	3
20 December 1996	736	1085	31.0	10	4

The particulate organic carbon content of the water (*POC*, equation (5.27)) is assumed to be constant at 0.2 mg C/l. This was the mean particulate organic carbon concentration in waters from reef flats in the Orpheus Island region of the Great Barrier Reef, monitored over a 2-year period by Klumpp and Griffiths (1994). This *POC* was in the range reported by many other studies around the Pacific (see Klumpp *et al.*, 1992) and was considered reasonable for nearshore fringing reefs in Solomon Islands (Klumpp, 1999, pers. comm.).

## 6.4 Summary

In this chapter, the economic and biological data used to estimate parameter values for the giant-clam production system model were described. The parameter and variable values used in base-model runs are summarised in Table 6.13. The derivation of biophysical parameter values is presented in the following chapter.

**Table 6.13. Parameter and variable values used in base-model runs**

Parameters	Value	Units
<i>Assumptions:</i>		
$CA$	5005	$\text{cm}^2$
<i>Economic:</i>		
$P_L$	1.50	SBDS\$/hr
$P_K$	43.38	SBDS\$/unit
$P_M$	0.95	SBDS\$/kg
$X_r$	0.25	US\$/SBDS
<i>Biological:</i>		
$N_0$	200	clam seed/cage
$w_0 (T. crocea)$	$1.313 \times 10^{-3}$	kg wet weight
$w_0 (T. derasa)$	$1.245 \times 10^{-3}$	kg wet weight
$\mu (T. crocea)$	0.0019	clams/cage/day
$\mu (T. derasa)$	0.00011	clams/cage/day
<i>Environmental:</i>		
$Lat$	10	latitude
$Z$	101	days after January 1
$D$	1.29	m
$V_{SD}$	14.18	m
$POC$	0.2	mg C/ $\ell$