Farming giant clams for the aquarium and seafood markets: a bioeconomic analysis

Oscar Cacho[a] and Robyn Hean[b]

[a]Graduate School of Agricultural and Resource Economics, University of New England, Armidale NSW 2351
[b]Farm Forestry Advisory Unit, NSW Agriculture, Tamworth NSW 2340

Contributed Paper to the 46th Annual Conference of the Australian Agricultural and Resource Economics Society
Canberra, Australian Capital Territory, 13-15th February 2002

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Giant clams offer small holders throughout the Indo-Pacific with good prospects for commercial culture to satisfy their increasing dependence on the cash economy. Two species appear promising for an emerging village-based export industry in Solomon Islands. These species are *Tridacna crocea*, the preferred species for the aquarium market, and *T. derasa*, the species that has the best potential for the seafood market. In this paper, a bioeconomic model is used in a normative analysis to explore optimal-management strategies for village farmers producing these clams. The normative study provides a benchmark against which current practices can be evaluated.

Keywords: aquaculture, giant clams, optimal management, bioeconomics

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Introduction

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 are characterised by a scaly shell and coloured mantle, and are unique by virtue of a symbiotic relationship with algae that reside within their mantle tissue and convert sunlight through photosynthesis into nutrients for the clam. They are essentially autotrophic, although they may supplement their nutrition by filter-feeding particulate organic matter from the surrounding seawater (Klumpp *et al.* 1992; Klummp and Griffiths 1994).

Commercial mariculture of giant clams has emerged over recent years in developing countries of the Indo-Pacific as a result of numerous research and development projects funded by organisations such as the Australian Centre for International Agricultural Research (ACIAR). A variety of mariculture techniques have been 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 marketing opportunities for maricultured giant clams have also been investigated and 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), Tisdell *et al.* (1994) and Riepen (1998). The three main markets identified so far are for aquarium specimens, seafood and shells. The only active market to date is the aquarium trade (Gervis *et al.* 1995). However, this market is limited in size and unlikely to be large enough to support commercial mariculture 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.

The International Center for Living Aquatic Resources Management (ICLARM) was involved in both research into mariculture techniques and market development, through a project aimed at the commercialisation of village-based giant-clam farming in Solomon Islands. Although civil unrest in that country has curtailed this project, ICLARM demonstrated that coastal village communities can successfully farm giant clams for the export market. ICLARM conducted this project through its Coastal Aquaculture Centre (CAC) which it established near Honiara in Solomon Islands in 1987. The focus of the project was a set of village-farming trials where selected villagers reared giant clams in ocean nurseries for commercial sale and experiments. The trials were designed to identify the optimal environmental conditions and farming techniques for village farming, and were based on the production of giant clams to test and develop new and existing markets. By the late 1990s, ICLARM was distributing seed clams to up to 50 village farmers spread across Solomon Islands, who were producing clams for aquarium specimens and seafood. ICLARM's approach to the project is described by Gervis *et al.* (1995) and Bell *et al.* (1997c). 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 farming systems are simple, low-cost and low-input operations. They typically involve rearing giant clams in sea cages raised above the sea floor on trestles 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. Labour input is used for planting, cleaning, thinning and harvesting. Planting involves placing the seed clams into cages and fixing the cages to trestles on a fringing reef. 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.

Although village farmers may not be profit-maximisers, it is of economic interest to undertake a normative study of their production system. This involves finding the set of controllable inputs that maximises a stream of discounted net benefits. The controllable inputs are clam-seed density and size, growing-cycle-length, and labour. 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 below, profit maximisation is taken as the only objective in this paper, as it provides a benchmark against which current practices can be evaluated. A bioeconomic model of giant-clam farming based on the well-developed forestry-rotation literature forms the basis of the study. The model is described in an optimising framework and is applied to explore optimal management of the giant-clam operation. The model is implemented for *T. crocea*, the preferred species for the aquarium market, and *T. derasa*, the species that appears to have the best potential for the seafood market (Bell *et al.*, 1997a; Bell *et al.*, 1997c; Hart *et al.*, 1998, 1999).

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 (years) which maximises the objective function:

$$\pi(T) = V(T)e^{-rT} \tag{1}$$

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 (1) is maximised when:

$$\frac{V'(T)}{V(T)} = r \tag{2}$$

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 (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:

$$\pi(T) = V(T)e^{-rT} + V(T)e^{-2rT} + V(T)e^{-3rT} + ... + V(T)e^{-\infty rT} \tag{3}$$

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

$$\pi(T) = \frac{V(T)}{e^{rT} - 1} \tag{4}$$

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

$$V'(T^*) = rV(T^*) + r\frac{V(T^*)}{e^{rT*} - 1} \tag{5}$$

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) 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:

$$\frac{V'(T^*)}{V(T^*)} = \frac{r}{1 - e^{-rT}} \tag{6}$$

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.

The Model

The model used in this paper comprises economic and biophysical models. 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. The economic model is described below, followed by a brief description of the biophysical model.

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 provided 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 incurred by ICLARM, since ICLARM did not charge the farmers the interest cost associated with this advance. This 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:

$$\pi_T = V_T\{h_T, \mathbf{u}, \mathbf{p}\}e^{-rT} \tag{7}$$

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

$$\mathbf{u} = [w_0, N_0, H, TF] \tag{8}$$

The price vector is:

$$\mathbf{p} = [P_C, P_S, P_L, P_K, P_M] \tag{9}$$

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):

$$V_T = R_T\{h_T, \mathbf{u}, \mathbf{p}\} - C_T\{h_T, \mathbf{u}, \mathbf{p}\} \tag{10}$$

$$R_T = \frac{P_C\{w_T\}}{X_r} h_T\{\mathbf{u}\} \tag{11}$$

$$C_T = P_S\{w_0\}N_0 + P_L L_T\{\mathbf{u}\} + P_K K_T\{\mathbf{u}\} + P_M h_T\{\mathbf{u}\} \tag{12}$$

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 **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 the space on 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 later.

The harvest is given by:

$$h_T = w_T\{\mathbf{u}\}N_T K_T \tag{13}$$

where w_T is the average weight (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 (14) and (18) respectively).

Biophysical Model

The biophysical model describes the average growth of an individual giant clam and survival within the population.

Growth

The growth component of the model is described in terms of an energy (carbon) budget. 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 filter-feeding. 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. Hean and Cacho (under review) describe the model in detail.

Inputs to the growth model are environmental and management variables and output is the time trajectory of clam weight. Environmental variables are solar radiation, which affects photosynthesis; particulate organic matter, which influences filter-feeding; and temperature, which impacts on both photosynthesis and respiration. Management variables are husbandry and thinning frequency. Husbandry is a subjective measure of cage cleanliness, measured on a scale from 1 (non-existent) to 5 (excellent), and is described by Hart *et al.*, 1998. The effect of management variables on growth is described below.

The growth model is dynamic and nonlinear and comprises a set of differential equations that are solved by numerical integration. It can be summarised as follows:

$$w_T = \int_0^T \rho_t\{\mathbf{u},t\}G_t\{\mathbf{u},t\}dt \tag{14}$$

where G_t is clam growth in terms of carbon (mg/d), ρ_t is a factor that accounts for carbon partition within the clam and converts carbon weight to clam weight and t is measured in days.

The value of w_T is affected by the decision variables in $\mathbf{u}$. Poor husbandry (H) 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). The effect of husbandry is captured through a ‘husbandry effect’ (HE), which is a multiplier on energy intake:

$$HE = 1 - \alpha_H \left| H - 5 \right| \tag{15}$$

The growth model was incorporated into a nonlinear least-squares routine and the parameter α_H (Table 1) was estimated from field data gathered by ICLARM for *T. crocea* and *T. derasa* over a period of two years from 12 and 14 trial sites respectively. The datasets for the species contained 266 and 643 observations respectively.

Infrequent thinning results in crowding and reduces the energy intake from photosynthesis, since the clam is not able to fully project its mantle as space becomes limiting. The effect of thinning frequency (TF) is captured through a ‘density effect’ (DE), which is a multiplier on photosynthesis:

$$DE_t = \frac{CA}{MA_t \; N_t} \tag{16}$$

where CA (cm^2) is the cage area and MA (cm^2) is the area taken up by the clam fully projecting its mantle. MA is described by:

$$MA_t = \alpha_M w_t^{\beta_M} \tag{17}$$

The parameters in this function were estimated based on published reports (Klumpp and Griffiths 1994; Klumpp and Lucas, 1994; Griffiths and Klumpp 1996).

Both HE and DE are constrained to the interval (0,1); under ‘ideal’ management (ie., excellent husbandry and frequent thinning) both multipliers will have a value equal to unity. Less than ideal management will reduce their value below unity and w_T will be correspondingly affected upon numerical integration of the model.

Survival

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. 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. Hart *et al.* (1998) also found regression models for survival were a poor fit to this data. 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:

$$N_t = \frac{N_0 e^{-\mu t}}{K_t} \tag{18}$$

N_t is the surviving number of clams per cage, μ is the daily mortality rate (clams per cage per day) and the other variables are as previously described.

Economic Inputs

The economic variables affecting giant-clam farm profitability include production costs and marketable clam prices. Data was gathered on inputs and costs 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.

Clams

Price estimates for clam seed produced by ICLARM were collected (see Gervis, 1995; Gervis *et al.*, 1995) and used to estimate step-price functions for *T. crocea* and *T. derasa* seed. These functions are presented in Figure 1 for both species. ICLARM sold seed to village farmers on credit and did not charge them the interest cost associated with this advance. ICLARM also delivered the seed to the farmers for free. These implicit subsidies would be unlikely to continue in a mature industry run by the private sector.

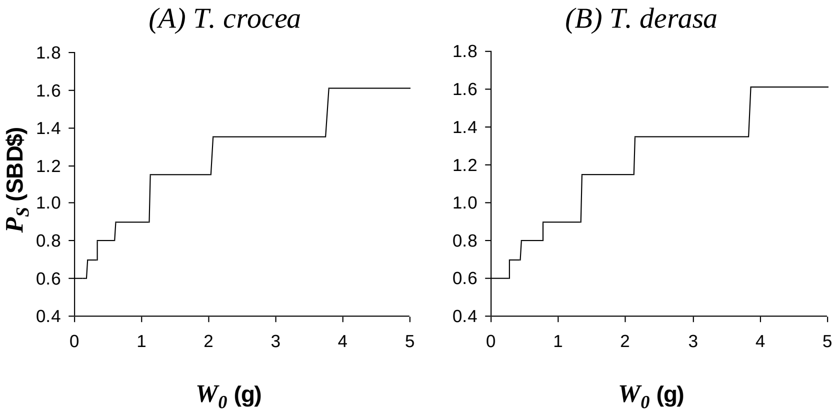


Figure 1. Step-price functions for clam seed for both species

Prices were also collected for marketable clams. Village farmers sold their marketable clams to ICLARM who facilitated their sale with local exporters in Honiara. In 1997, the only active market for giant clams was the aquarium market. There was, and continues to be, no established market for seafood clams. Hence there is much uncertainty about the prices that will emerge for seafood clams. The estimated price functions for marketable clams are presented in Figure 2 for both for *T. crocea* and *T. derasa*. It is assumed that *T. derasa* less than 15 cm in shell length (or 0.38 kg) are not saleable (see Bell *et al.*, 1997a). In the model, these prices are converted from US$ to SBD$ (see equation (11) and Table 1).

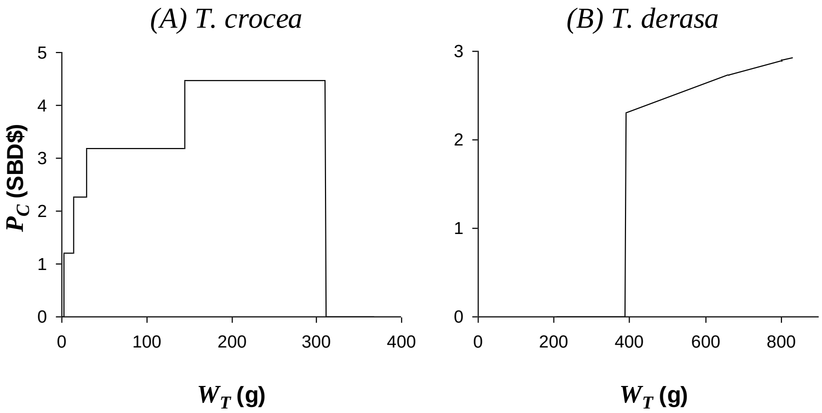


Figure 2. Price functions for marketable clams for both species

In the base-model runs, the weights of the *T. crocea* and *T. derasa* seed (w_0) were assumed to be 1.313 x 10^{-3} kg and 1.245 x 10^{-3} kg respectively (Table 1), the mean seed weights in ICLARM's trials. The corresponding prices were SBD$1.15 and SBD$0.90. In the base model, only one cage of clams is planted with 200 seed, at the start of the planning horizon; thus N_0=200 (Table 1). This is consistent with the number of clam seeds planted per cage in ICLARM's trials. Both w_0 and N_0 can be treated as decision variables in the model, but they are maintained at their base values in this paper. The mean daily mortality rate (μ) was estimated to be 0.0019 clams/cage/d and 0.00011 clams/cage/d for *T. crocea* and *T. derasa* respectively, based on information in *Hart et al*. (1998).

Table 1. Parameter and variable values used in base-model runs

Parameters	Value		Units
Assumptions:			
CA	5005		cm^2
Economic:			
P_L	1.50		SBD$/hr
P_K	43.38		SBD$/unit
P_M	0.95		SBD$/kg
X_r	0.25		US$/SBD$
r	0.06		–
Biological:			
N_0	200		clam seed/cage
	T. crocea	*T. derasa*	
w_0	1.313 x 10^{-3}	1.245 x 10^{-3}	kg wet weight
α_H	0.0185	0.0144	–
α_M	16.7507	17.5318	cm^2
β_M	0.6392	0.7777	–
μ	0.0019	0.00011	clams/cage/day

Labour

Estimating the labour input and the relationship between labour and the decision variables 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. The intensity with which these activities are undertaken depends on the stage in the production cycle, the number of clams (N_0 and N_t), the husbandry level (H), the frequency of thinning (TF) and the final weight of the clams (w_T).

The labour input was estimated for each activity on a per cage or per clam basis (Table 2). Cleaning labour was particularly troublesome to estimate given there is a relationship between the time spent cleaning and the cleanliness of the cages. Following discussions with ICLARM staff, the relationship between labour and husbandry was assumed to be linear.

Table 2. Labour input for giant-clam production

Activity (i)	Labour input (L_i)	Units
Planting	0.5	hrs/cage
Cleaning	$0.0036\,(H-1)$	hrs/day/cage
Thinning	0.025	hrs/clam
Harvesting	0.05	hrs/clam

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 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. 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. An optimistic net return to labour for copra production was estimated to be SBD$1.50/hr and used as the opportunity cost of labour, or wage rate (P_L).

Capital

Giant-clam farming requires both variable and fixed capital inputs. The former comprise cages and trestles, the later include goggles, mask, snorkel, scrubbing brush, harvest knife, pliers, wire cutters, cement trowel, callipers and a portable cooler. Fixed inputs are required irrespective of the scale of clam production and have no influence on optimal model solutions.

The amount of capital required on the farm at any one time depends on the extent of planting, thinning and harvesting. It does not depend explicitly on species, but species that grow larger and more rapidly require more thinning, which affects capital input. Mortality of the clams in the cages may also affect the need for thinning and thereby farm capital. *T. derasa* has good growth and survival, suggesting that this species may need to be thinned most frequently. The area of a "standard" cage (CA) was taken to be 5005 cm^2.

In the base-model runs, one cage is planted at t=0 with 200 seed clams (N_0). 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) up to a maximum of 16 cages/farm, which would accommodate the seed clams at the end of the production cycle if they were all to survive.

The cost of capital (P_K) was estimated to be SBD$43.38 for a standard cage comprising one cage plus one quarter of a trestle. ICLARM provided construction materials to village farmers on credit, and did not charge them the interest cost associated with this advance, representing an implicit subsidy.

Marketing services

Marketing services include internal transport and airfreight of harvested clams from the farm to the exporter in Honiara. The village farmer covers these costs. 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 *T. crocea*.

Most farmers transport their clams by boat from their farm to a regional airport where an intermediary arranges their airfreight to Honiara. 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.

Transporting clams by boat can be a time-consuming activity for village farmers. Alternatively, they 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, but is used as a proxy for the fixed cost of boat transport. Internal airfreight can also be very costly; in 1997 most farmers were paying SBD$0.95/kg (Tafea, 1997, pers. comm.) and this was taken as P_M (Table 1).

Model Implementation

The model was implemented for both *T. crocea* and *T. derasa* using the base-case parameter values in Table 1 and price functions in Figures 1 and 2. A discount rate (r) of 6 percent was assumed throughout.

The optimal cycle-length for a single harvest was estimated by maximising equation (7) with respect to T (harvest time, years), while the optimal cycle-length for multiple harvests was estimated over an infinite time horizon by maximising the function:

$$\pi_T = V_T\{h_T, \mathbf{u}, \mathbf{p}\}\frac{1}{e^{rT} - 1} \tag{19}$$

The initial seed weight (w_0) and number of seed-clams planted per cage (N_0) were maintained constant at their base-case values, while the other two decision variables, husbandry (H) and thinning frequency (TF), were allowed to vary. A 5×7 factorial design with five levels of H (1, ..., 5) and seven levels of TF (26, 52, 78, 104, 156, 208, 260 weeks) was used. Results were compared based on optimal cycle-length (T^*) for the single clam harvest, and also on maximum profit obtained (π^*), labour usage (L^*), total clam harvest (h^*) and the shell length of the clams at harvest (SL^*) for multiple harvests.

Single-cycle optimisation

The model was initially solved for a base case of ideal management, consisting of excellent husbandry (*H*=5) and frequent thinning (*TF*=26), over a period of five years for *T. crocea* and 15 years for *T. derasa*. These periods were considered long enough to capture the optimal cycle-lengths for the respective species. For the base case, mortality was assumed to be zero.

The present value of profits from harvesting at any time during these periods are presented in Figures 3 (A) and 4 (A) for *T. crocea* and *T. derasa* respectively, for the base case and for two cases of less frequent thinning (*TF*=52, 208). These are plots of the objective function given by equation (7). Because the profit functions for *T. crocea* and *T. derasa* are not continuously differentiable, it is not possible to solve for their optimal cycle-lengths using the Fisher rule (equation (2)). However, for any given pair of values for *H* and *TF*, the optimal cycle-length can be approximated by evaluating a plot of the objective function or by finding the maximum value in a vector of simulation results. For the base case, the optimal cycle-length (T^*) is at 3.15 years for *T. crocea* and 1.98 years for *T. derasa*. The maximum profits are SBD$1,973 and SBD$1,035 in present value terms for *T. crocea* and *T. derasa* respectively. These values correspond to the maximum points on the graphs for the base case (*TF*=26) in Figures 3 (A) and 4 (A) respectively. It is clear from the other two graphs for less frequent thinning (*TF*=52, 208) that different thinning frequencies affect the shape of the profit function (due to the cost of new cages); this is also the case for different levels of husbandry although this is not shown here.

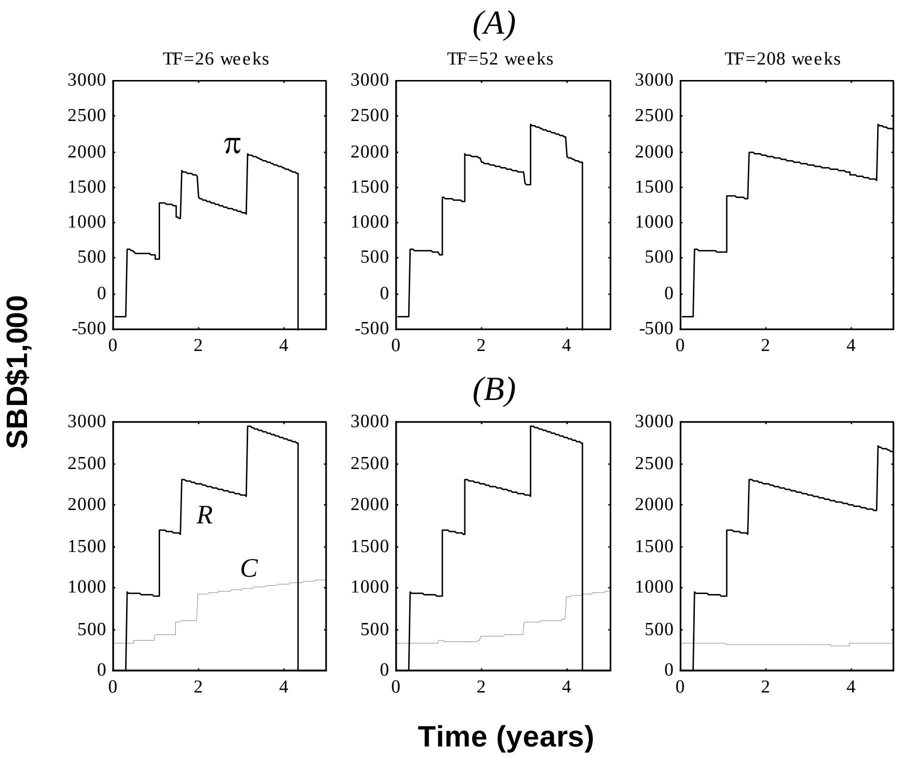


Figure 3. (A) Present value of profits (*π*) and (B) present value of revenues (*R*) and costs (*C*) for *T. crocea* for the single-cycle case with zero mortality

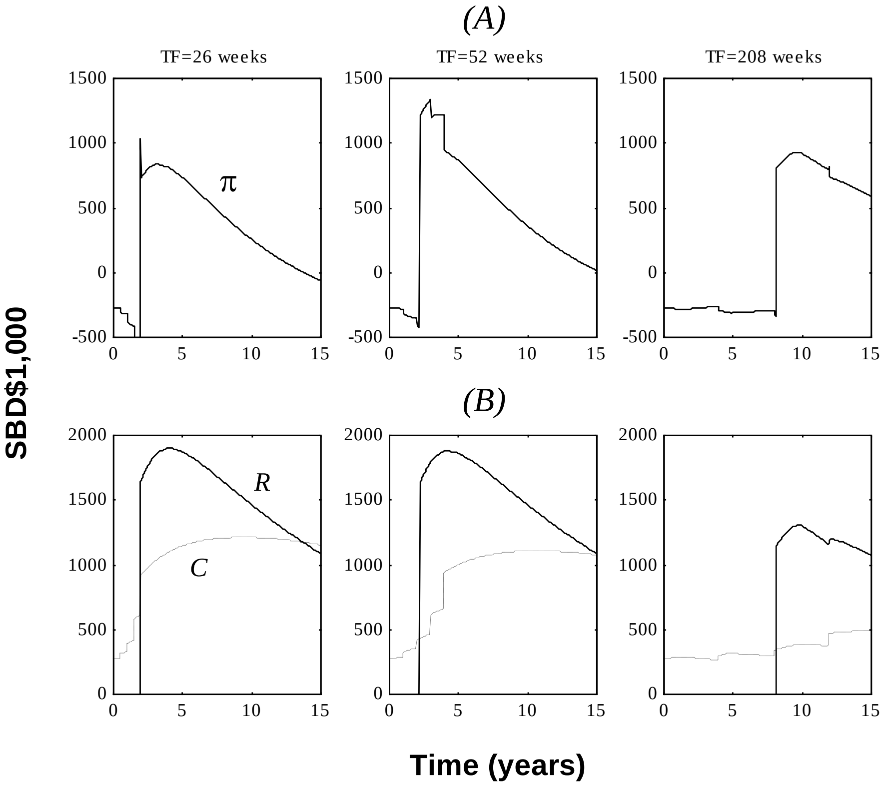


Figure 4. (A) Present value of profits (*π*) and (B) present value of revenues (*R*) and costs (*C*) for *T. derasa* for the single-cycle case with zero mortality

The jagged shape of the profit function for *T. crocea* (Figure 3 (A)) is due to the step-wise nature of discounted revenues and costs (Figure 3 (B)), which in turn are determined by the step-wise price function for marketable clams of this species (see Figure 2), and the impact of thinning as already discussed. The shape of the function for *T. derasa* (Figure 4) is not as jagged once the clams reach marketable size, because of the linear price function assumed for the marketable clams of this species.

The spike in profits for *T. derasa* (Figure 4 (A)) warrants further explanation. The clams reach marketable size one week prior to the next thinning. There is a significant increase in revenues (Figure 4 (B)), and a corresponding increase in profits (Figure 4 (A)), when the clams reach 15 cm in shell length. This occurs after 1.98 years, or 103 weeks, of grow-out. The following week (after 2 years or 104 weeks), thinning is undertaken and the number of cages on the farm increases from 8 to 16. There is a substantial increase in costs (Figure 4 (B)) and a corresponding reduction in profits (Figure 4 (A)).

Solving the optimal cycle-length model for the selected combinations of the decision variables *H* and *TF* gives a look-up table for each species for the optimal cycle-length in the single-cycle case. The model was first solved for zero mortality and the results are shown in Table 3.

In the zero-mortality case for *T. crocea*, T^* is unaffected by thinning frequency when husbandry is very poor (*H*=1) (Table 3). This is because the clams grow slowly and do not become crowded. When husbandry is better (*H*>1), T^* is affected by *TF* when thinning is infrequent. The clams grow quickly and do become crowded. If *TF* is 208 weeks, crowding results in an increase in T^* and the clams are harvested at a larger size; however, if *TF* is 260 weeks, crowding reduces T^* and the clams are harvested at a smaller size. In the latter case, the opportunity cost of keeping the clams in the water (the returns from harvesting a smaller clam) outweighs the returns that could be obtained from delaying harvest until the clams are larger (the opportunity cost of harvesting earlier).

Table 3. Optimal cycle-length (T^*, years) for the single-cycle case for both species, with zero mortality

T. crocea

TF (weeks)	*H* (scale) 1	2	3	4	5
26 to 104	2.74	4.39	3.87	3.49	3.15
156	2.74	4.39	3.99	3.78	3.68
208	2.74	4.99	4.81	4.68	4.62
260	2.74	2.30	1.99	1.78	1.61

T. derasa

TF (weeks)	*H* (scale) 1	2	3	4	5
26	4.97	4.28	3.95	3.34	1.98
52	2.97	2.97	2.97	2.97	2.97
78	4.37	4.37	4.43	4.47	4.47
104	5.93	5.91	5.95	5.95	5.73
156	7.33	7.90	8.96	7.94	7.75
208	9.34	9.93	9.93	9.92	9.76
260	11.93	11.93	11.87	11.95	11.72

In the zero-mortality case for *T. derasa*, T^* is affected by thinning frequency at all levels of husbandry due to the effect of crowding (Table 3). As thinning becomes infrequent, crowding generally increases T^* because the clams take longer to grow to their marketable size (15-cm shell length). In these cases, the returns that can be obtained from harvesting later when the clams are a marketable size (the opportunity cost of harvesting earlier) outweigh the opportunity cost of delaying harvest (the returns from harvesting earlier when the clams are below marketable size). Husbandry has little effect on T^* except when thinning is every 26 weeks, in which case better husbandry reduces T^* because the clams grow quickly to their marketable size.

The model was also solved for the mortality rates presented in Table 1; the results are presented in Table 4. Mortality ameliorates the effect of crowding evident in the zero-mortality case for both species. For *T. crocea*, the value of T^* is the same for infrequent thinning in the positive-mortality case as it is for frequent thinning in the zero-mortality case for all levels of husbandry. For *T. derasa*, the value of T^* is reduced in the positive-mortality case for all combinations of *H* and *TF* for which crowding has an effect in the zero-mortality case. For *T. crocea*, mortality also reduces T^* when thinning is every 26 weeks; profits are maximised earlier even though fewer clams are harvested.

Table 4. Optimal cycle-length (T^*, years) for the single-cycle case for both species, with positive mortality

T. crocea

TF	*H* (scale)				
(weeks)	1	2	3	4	5
26	1.94	1.63	0.44	1.78	1.61
52 to 260	2.74	4.39	3.87	3.49	3.15

T. derasa

TF	*H* (scale)				
(weeks)	1	2	3	4	5
26	4.97	4.28	3.95	3.34	1.98
52	2.97	2.97	2.97	2.97	2.97
78	4.33	4.33	2.97	2.84	2.68
104	3.85	3.97	3.34	3.13	2.97
156	4.49	4.30	4.14	4.08	3.99
208	5.73	5.27	5.22	5.10	5.02
260	6.46	6.35	6.27	6.12	6.06

Multiple-cycle optimisation

Equation (19) was applied to estimate the optimal cycle-length in the multiple-harvest case. The present value of profits over time for the base case considered above and for poor husbandry (H=1) are presented in Figures 5 and 6 for *T. crocea* and *T. derasa* respectively. The present value of profits for two cases of less frequent thinning (TF=52, 208) are also shown.

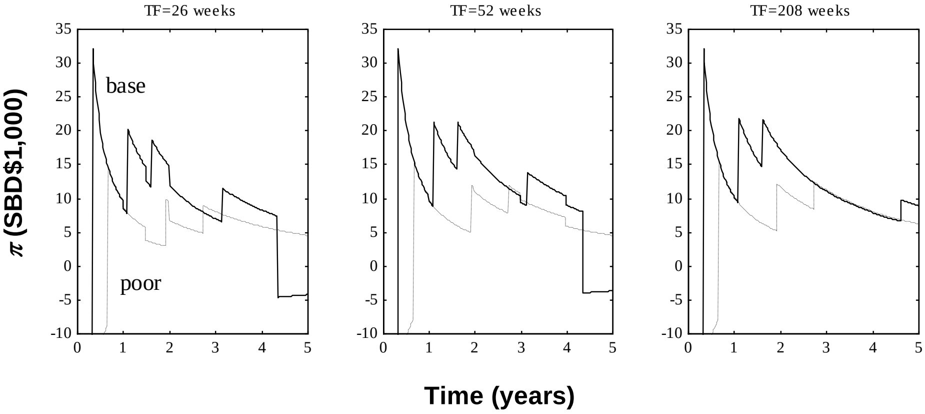


Figure 5. Present value of profits (π) for the base case (solid line) and for poor husbandry (dotted line) for *T. crocea* for multiple cycles

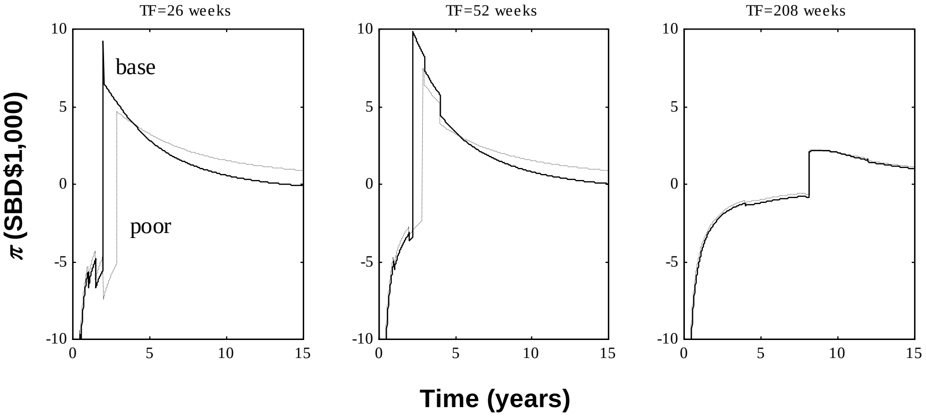


Figure 6. Present value of profits (π) for the base case (solid line) and for poor husbandry (dotted line) for *T. derasa* for multiple cycles

For *T. crocea* (Figure 5), the optimal cycle-length for the base case is now only 0.33 years, compared to 3.15 years for the single cycle. For poor husbandry, T^* is 0.67 years. These values correspond to the maximum points on the graphs for the base case (*TF*=26) in Figure 5, where the present value of profits is SBD$32,068 and SBD$14,608 for good and poor husbandry respectively. For *T. derasa* (Figure 6), the optimal cycle-length for the base case is unchanged from 1.98 years, and it increases to 2.88 years with poor husbandry. Profits at these maximum points are SBD$9,261 and SBD$4,638 respectively (Figure 6).

Optimal results for the five husbandry levels and 52-weekly thinning for the multiple-cycle case are presented for *T. crocea* and *T. derasa* in Table 5 for zero mortality. For both species, the present value of profits at each husbandry level is maximised at this thinning frequency. Results are presented for optimal cycle-length (T^*), present values of profit (π^*), labour usage (L^*), total clam harvest (h^*) and the harvest shell length of the clams (SL^*).

In Table 5, T^* decreases with increasing husbandry, and both *T. crocea* and *T. derasa* are harvested soon after they reach their marketable sizes of 2.54-cm and 15-cm shell length respectively. For both species, the additional returns from delaying harvest are too low to warrant keeping the clams in the water until they are a larger size. h^* is therefore fairly constant for both species. T^* is so short for *T. crocea* that there is insufficient time for thinning to be undertaken and labour is used for husbandry alone. T^* is some 2 years longer for *T. derasa* and thinning is undertaken. For both species, L^* and π^* increase with increasing husbandry, and are highest when husbandry is excellent (*H*=5).

Mortality has no effect on the optimal cycle-length of both species. For *T. crocea*, all other results are also unchanged; for *T. derasa* they are slightly reduced. This is not shown here. For both species, π^* is again maximised when *H*=5 and labour usage is greatest.

As explained earlier, the optimal cycle-length should be shorter in the multiple-cycle optimisaton, so long as the opportunity cost of delaying the harvest, in equation (5), is positive. The expected results were obtained for both *T. crocea* and *T. derasa*, except for some combinations of the decision variables for which T^* is the same for both the multiple- and single cycles (indicating that the opportunity cost is zero). The single-cycle solutions therefore overestimate the optimal cycle-length for most combinations of the decision variables because the opportunity cost (ie. the productive value of the site) is not taken into account. T^* under multiple-cycle management was, on average, only 57 percent of T^* under single-cycle management. When reseeding is possible, it is optimal to harvest at shorter intervals. This is illustrated in Figure 7 for the base-case thinning frequency of 26 weeks. At a husbandry of five in Figure 7 (B), *T. derasa* grow to their marketable size so quickly that the opportunity cost of delaying the harvest is zero, and the clams are harvested soon after they reach 15-cm shell length for both the multiple and single cycles. Thus, when H=5, T^* is equal in both cases.

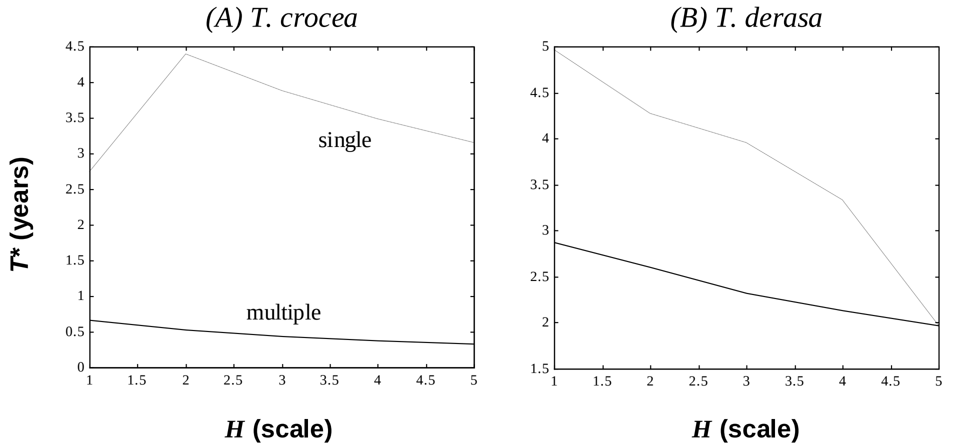
Table 5. Optimal results for the multiple-cycle case for both species, for 52-weekly thinning with zero mortality

T. crocea

H (scale)	T^* (years)	π^* (SBD$)	L^* (hr/cage/year)	h^* (kg)	SL^* (cm)
1	0.67	15477	15.6	0.58	2.54
2	0.54	19393	20.9	0.59	2.55
3	0.44	23652	26.4	0.59	2.55
4	0.38	27224	31.3	0.60	2.57
5	0.33	32068	37.4	0.59	2.55

T. derasa

H (scale)	T^* (years)	π^* (SBD$)	L^* (hr/cage/year)	h^* (kg)	SL^* (cm)
1	2.88	7441	5.4	76.27	15.02
2	2.61	8224	8.7	76.59	15.04
3	2.32	9260	11.5	76.05	15.01
4	2.21	9770	13.8	76.72	15.05
5	2.19	9820	16.1	76.88	15.06

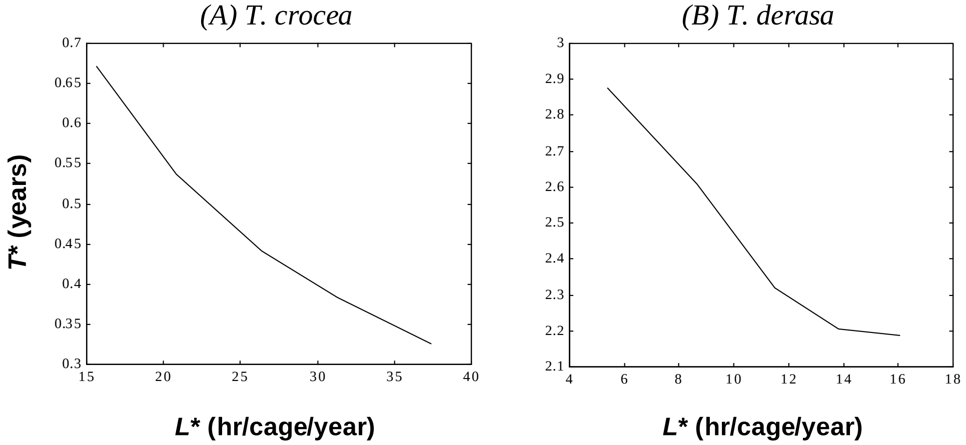

(A) T. crocea

(B) T. derasa

Figure 7. Optimal cycle-length (T^*) for the multiple-cycle case (solid line) and for the single-cycle case (dotted line) for both species, for 26-weekly thinning with zero mortality

Input substitution

Labour usage increases as cycle-length decreases, indicating that labour and time are substitute inputs in production (Figure 8). For these optimal solutions, the level of production is not exactly the same, hence this only approximates an isoquant. This is illustrated in Table 5, where total clam harvest varies slightly with the different levels of husbandry (h^* ranges between 0.58 and 0.60 kg for *T. crocea*, and between 76.05 and 76.88 kg for *T. derasa*).



(A) T. crocea

(B) T. derasa

Figure 8. Substitutability between optimal labour usage (L^*) and optimal cycle-length (T^*) for both species, for 52-weekly thinning with zero mortality

The slope of the curve for *T. crocea* (Figure 8 (A)) means that, under optimal management, time from planting to harvest can be decreased by 0.016 years (5.7 days) for each additional hour of labour used per cage seeded. In the case of *T. derasa* (Figure 8 (B)), optimal cycle-length can be decreased by 0.064 years (23.5 days) for each additional hour of labour used per cage seeded.

Village farmers may not be profit maximisers, and labour spent on giant-clam farming takes them away from other activities. Rather than investing more labour and harvesting the clams earlier, a village farmer with other objectives may devote less labour to giant-clam production and harvest the clams later, and spend more time on other activities (including leisure).

Global optimisation and sensitivity analysis

In order to find the global maximum, and use the bioeconomic model in sensitivity analysis for a selection of economic and biological parameters, the model was solved as a non-linear programming (NLP) problem using a sequential quadratic programming algorithm (Mathworks, 1996). As discussed by Cacho (1998) regarding numerical solutions to bioeconomic models using NLP, a common problem with complex NLP models is the difficulty of finding the global maximum; this was experienced in this analysis.

The NLP was combined with a genetic algorithm (GA) in an attempt to overcome this problem. GA, based on the evolution of populations of living organisms, is a technique that may be used to maximise functions that are highly nonlinear (Cacho and Simmons, 1999). By combining GA and NLP, the possibility of converging to a local maximum can be reduced. Unfortunately, this combined approach also failed to perform. Hence, the look-up technique explained before was used instead.

When incorporated into sensitivity analysis, model results for the optimal decision variables and cycle-length were found to be insensitive to changes in the values of the economic parameters (r, P_L, P_K, P_M, X_r) and biological parameters (α_M, μ) considered. This is possibly because the price of marketable clams is so high relative to the cost of inputs in production. Given the stability of the optimal solutions for a wide range of parameter values, no further sensitivity analysis is presented. Due to the low opportunity cost of labour and the low cost of the farming operation as a whole, the price of marketable clams would have to decrease substantially before the sensitivity analysis on economic variables becomes interesting. This would have required extreme assumptions about demand that would not have contributed much to the analysis given the uncertainty about how the markets for giant-clam products will develop.

Summary and conclusions

In this paper, a bioeconomic model is developed and applied in a normative analysis to explore optimal management of smallholder mariculture of giant clams, *T. crocea* and *T. derasa*, farmed for the aquarium and seafood markets respectively. Optimal management involves finding the combination of husbandry, thinning frequency and cycle-length that maximises a stream of discounted net benefits. Although village farmers may not be profit maximisers, a normative study provides a benchmark against which current practices can be evaluated. The model is solved for a single clam-production cycle to demonstrate the shape of the profit function for the two species, and to develop a satisfactory technique for solving the optimisation model for multiple clam-production cycles.

The results of simulation modelling suggest that for *T. crocea*, maximum profits are obtained when husbandry is excellent and the cycle-length is so short (around 4 months) that thinning is not undertaken. For *T. derasa*, maximum profits are also achieved with excellent husbandry, however the optimal cycle-length is longer (just over 2 years) and annual thinning is undertaken. Thinning is necessary for optimal management of *T. derasa* due to the effects of crowding over the longer cycle period; this is unaffected by mortality. In general, these results are consistent with the extension advice provided to village farmers by ICLARM.

For both species, maximum profits are obtained when labour usage is most intensive. This outcome is partly due to the low opportunity cost of labour, which is based on copra production, the most likely alternative source of cash income for smallholders, and occurs under unconstrained profit maximisation. Even though the opportunity cost of labour is low, labour spent on giant-clam farming takes villagers away from other activities. Hence, the scale of the giant-clam operation based on the profit-maximising solutions may be constrained by labour availability. Labour and cycle-length are substitute inputs in production however, so the village farmer with other objectives will be able to use less labour and a longer cycle-length, and have more time to devote to other activities.

This analysis also shows that, although the traditional forestry model provides a solid theoretical base to the optimisation model, its direct application is not possible because of the step-wise shape of the profit functions of the species considered.

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