Evaluating externalities using bioeconomic techniques: the impact of forestry on mariculture

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

Abstract

In this paper, a bioeconomic model is used to investigate possible externalities imposed by forestry on giant-clam farming in Solomon Islands. This is of economic interest due to the rapid expansion of forestry in that country and the potential for mariculture to become an important source of cash income for village communities. Forestry may result in externalities through sediment run-off, which has a complex array of effects on the seawater in which giant clams are farmed, such as nutrient enrichment and turbidity. These effects are unknown because empirical studies in the field and experimental research in the laboratory have not been done. In the absence of this information, simulation modelling provides insight into the economic implications of the possible effects of sedimentation on the production system.

Keywords: mariculture, giant clams, externalities, bioeconomics

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Introduction

Mariculture may be threatened by land-based activities such as forestry through sedimentation. In the absence of scientific information about the effect of sediments on the production system, simulation modelling can be used to gain insights into externalities that may result from sediment run-off that increases the nutrient concentration and turbidity of seawater in which marine animals are farmed

A bioeconomic model is used in this paper to explore the possible impact of sedimentation on optimal management of giant-clam mariculture. The model is applied as a case study to village farming in Solomon Islands where the forestry industry has expanded rapidly, and the mariculture of giant clams and other marine animals shows potential to become an important source of cash income for village communities.

Giant clams (family *Tridacnidae*) are bivalve molluscs that occur naturally only in the tropical and subtropical marine waters of the Indo-Pacific. Rosewater (1965, 1982) and Lucas (1988) describe them. They are unique by virtue of a symbiotic relationship with algae that reside within their coloured 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 on 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. These projects have been funded by organisations such as the Australian Centre for International Agricultural Research (ACIAR), and many have had the ongoing involvement of the International Centre for Living Aquatic Resources Management (ICLARM).

During the 1990s, ICLARM conducted mariculture trials in Solomon Islands 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 techniques for village farming, and were based on the production of giant clams to test and develop new and existing markets. 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); a market is emerging for seafood (Bell *et al.* 1997a).

By the end of the decade, ICLARM was distributing “seed” clams to up to 50 village farmers spread across Solomon Islands, who were producing clams for aquarium specimens and seafood. Gervis *et al.* (1995) and Bell *et al.* (1997c) describe ICLARM’s approach to the trials. 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). Although civil unrest has curtailed the trials, ICLARM has demonstrated that smallholders can successfully farm giant clams for the export market.

The farming systems are simple, low-cost and low-input operations. They typically involve rearing 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. Inputs to production are environmental and management variables. Management variables determine the amount of labour and capital (ie. cages) used on the farm. Labour is used for planting cages with seed clams; cleaning cages of predators and algal build-up; thinning clams into an increasing number of cages as the clams grow; and harvesting clams of marketable size and preparing them for transport and sale. Due to the autotrophic nature of giant-clam nutrition, no feeding is required.

Below, the interaction between forestry and mariculture is described, and the possible effects of sedimentation on giant-clam production are considered. The bioeconomic model used for the analysis is then explained. It is implemented for *Tridacna 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), for a range of environmental conditions.

Background

Small developing island economies such as Solomon Islands are heavily dependent on their natural-resource base for land-based activities such as forestry, agriculture and tourism, and water-based activities such as fishing and mariculture. This is depicted in Figure 1.

Forestry and fisheries are the two biggest export earners in Solomon Islands (Leary, 1992), while agriculture and tourism are a minor part of the economy. Most of the population enjoys self-sufficiency from subsistence gardening and fishing. Mariculture of giant clams and other marine products, such as corals, pearl oysters and beche-de-mer, on fringing coral reefs may become an important source of cash income for village communities (Bell and Gervis, 1999).

Forestry and agriculture are a significant threat to fisheries and mariculture through sediment run-off that may result in externalities. Richmond (1994) and Kinsey (1986) discuss the effects of sedimentation on coral reefs. Tourism may also result in degradation of coastal environments suitable for fisheries and mariculture if access is unrestricted and the resource is ill treated.

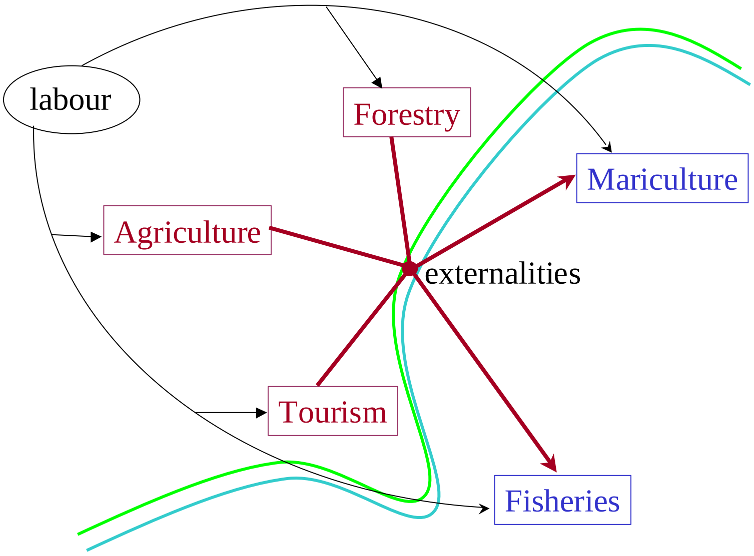

Figure 1. The big picture

There is a high level of interdependence between the environment and the economy in Solomon Islands (Thistlethwaite and Davis, 1996) and land- and water-based activities compete for environmental and labour inputs. From the government's standpoint the allocation of labour between competing uses may be an important question, as it will be influenced by policy that affects the relative size of each activity. However, in this paper only the forestry externality on mariculture is studied.

Forestry is a rapidly expanding export industry in Solomon Islands (see Davis and Abbott, 1989; Bennett, 1995; Montgomery, 1996). Although regulations to achieve sustainable resource use are in place, human resources to monitor forestry operations are limited and traditional resource owners are unaware of the effects that forestry may have on the sustainable use of their land and the productivity of nearby coral reefs (Bell, 1999, pers. comm.). This has contributed to destructive forestry practices (eg. clear felling, silviculture that leaves bare soil exposed) being undertaken in Solomon Islands. Such practices may substantially increase sediment run-off during rain events and alter the quality of the water draining from the forest through nutrient leaching and turbidity. Much has been written about the implications of destructive forestry practices (see Binkley and Brown, 1993; Lull *et al.*, 1995; Reynolds *et al.*, 1995; Zulkifli *et al.*, 1987).

Studies have found that nutrients enhance clam growth and survival (Hawkins and Klumpp, 1995; Solis *et al.*, 1988). Giant clams reared in turbid seawater have also been found to have poor growth and survival (Belda *et al.*, 1988; Gomez and Belda, 1988). The possible impact of sediment run-off from forestry operations on the giant-clam production system is therefore an important economic issue.

The sediment problem

The sediment problem involves a complex array of effects. A simplified representation of the problem is presented in Figure 2. Sediment is a convenient term used here to represent particulate in general that can be transported from land to sea by run-off following rain events.

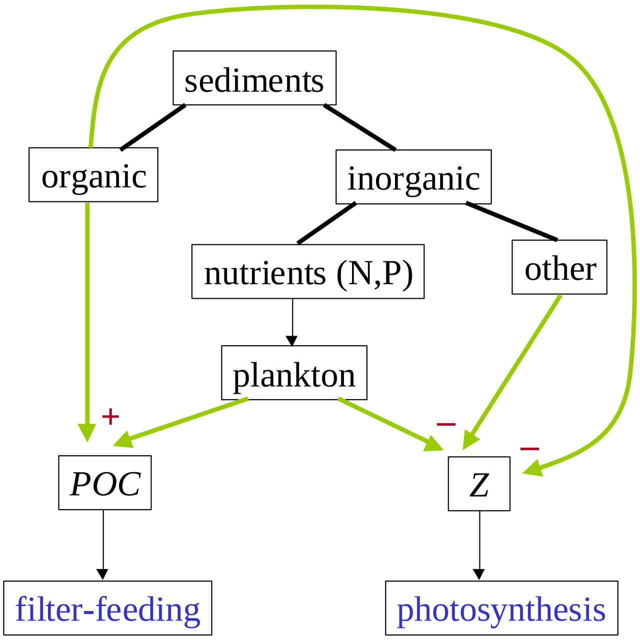

Figure 2. The sediment problem

In Figure 2, sediment can affect giant-clam production in two ways, through the particulate organic carbon content of the seawater (*POC*, mg C/ℓ) and the turbidity of the seawater (measured in terms of Secchi disk visibility[1], *Z*, m). *POC* affects the

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[1] 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

energy intake of the clam from filter-feeding and *Z* affects the light reaching the clam for photosynthesis.

Sediment from land-based activities such as forestry may be organic or inorganic. Organic sediment may affect both *POC* and *Z*. Inorganic sediment may be in the form of nutrients such as nitrogen and phosphorous which may stimulate plankton blooms and also affect both *POC* and *Z*. Some inorganic sediment (such as silt, sand and clay) may have no nutritional value and may only affect *Z*. Sediment may therefore have a positive or negative effect on the metabolic processes of photosynthesis and filter-feeding depending on its composition.

Modelling this simplified problem requires scientific information that is currently not available. The type of information that is needed includes:

- the effect of forestry practices and rainfall on sediment run-off;
- sediment composition;
- the contribution of organic matter and plankton to *POC*;
- the effect of organic matter on *Z*;
- the effect of nutrients on plankton blooms; and
- the effect of silt on *Z*.

It is also likely that sedimentation involves a much greater and more complex array of effects than have been included here. These effects are unknown because empirical studies in the field and experimental research in the laboratory have not been done. For example, silty inorganic sediments may affect the nutritional quality of organic sediments, in some cases positively by aiding the clam's digestion and other cases negatively by overloading the clearing capacity of the clam's filter-feeding mechanism. Up to some critical level, silt may enhance energy intake, then become a tax. Both organic and inorganic sediments that provide nutrition for the clam's symbiotic algae may also enhance giant-clam production. The real system is obviously more complicated regarding the impact of sediments than the present model, which treats explicitly only some effects in general terms.

In the absence of more substantial scientific information, simulation modelling can be used to gain insight into the possible effect of sediment on the giant-clam production system.

Conceptual Model

The model used in this paper may be represented by Figure 3. The model comprises biophysical and economic models. The biophysical model describes the average growth of an individual giant-clam and survival within the population. The economic model describes the costs and revenues associated with farming the population from planting through to harvest, and provides the link between the production system,

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measure of transparency. The greater the turbidity of water, the smaller the Secchi disk visibility (Boyd, 1979).

market prices and resource costs. Production is simulated by the biophysical model and used by the economic model to estimate profitability of the farming system in present-value terms.

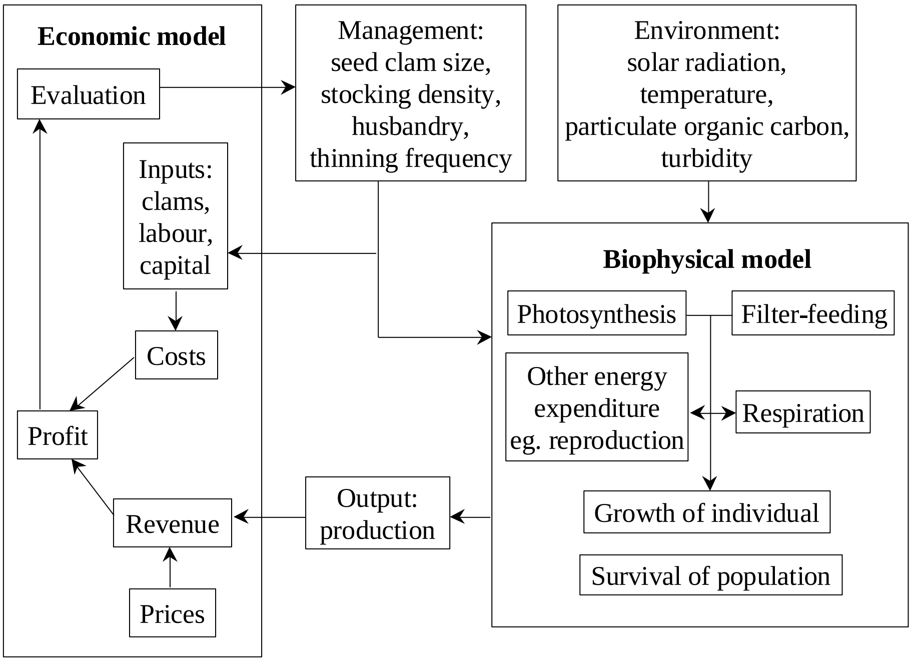

Figure 3. Conceptual representation of the bioeconomic model

Inputs to the model are environmental and management variables. Both influence production; management variables also influence the amount of labour and capital used on the farm. Due to inconclusive evidence regarding the effects of environmental and management variables on mortality, survival is described in the model by a decay function (see Hean and Cacho, 2002, under review b).

Environmental variables in the model are solar radiation, temperature, particulate organic carbon content and turbidity of the seawater. They impact on growth through the metabolic processes of photosynthesis, filter-feeding, and respiration (see Hean and Cacho, under review a). Other environmental variables such as salinity are assumed to not be limiting and are omitted from the model.

Management variables in the model are seed clam size, stocking density at planting, husbandry and thinning frequency. Husbandry relates to cage cleaning, and is measured on a scale from 1 (non-existent) to 5 (excellent), and is described by Hart *et al.*, 1998. A low husbandry level may inhibit clam growth through algal build-up in the cage (Bell *et al.*, 1997b). As already mentioned thinning involves reducing the number of clams per cage (increasing the number of cages) as the clams grow, and is undertaken to avoid the negative effects of crowding on growth.

Management variables determine the labour and capital used in production. Both husbandry and thinning require labour; thinning also affects the capital used on the farm. When the model is used in normative (optimising) mode as illustrated in Figure 3, where estimated profits are evaluated iteratively until they are maximised, husbandry and thinning also influence the optimal harvesting cycle-length, through their effect on clam growth. The cycle-length in turn affects the amount of labour and capital used, because it sets the period over which husbandry and thinning are undertaken.

The performance objective can be extended from profit maximisation to cover other objectives but this is not done here. When the model is used in simulation (positive) mode, optimisation is not the objective; the model is run for any given set of scenarios and the resulting profits are evaluated and compared.

Mathematical Model

In the model, the objective function to be maximised is given by:

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

where π_T is the present value of the profit, V_T (Solomon Island dollars, SBD$), from harvesting the clams at a cycle-length of T (years) over an infinite time horizon, h_T is total clam harvest (kg) at T, **u** and **p** are vectors of decision variables and prices, respectively, and r is the discount rate.

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:

$$\mathbf{u} = \left[w_0, N_0, H, TF\right] \tag{2}$$

The price vector is:

$$\mathbf{p} = \left[P_C, P_S, P_L, P_K, P_M\right] \tag{3}$$

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

The harvest is given by:

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$$h_T = w_T\{\mathbf{u}\}N_T K_T \tag{4}$$

where w_T is the average weight (kg) of the clams harvested, N_T is the number of clams harvested per cage and K_T is the amount of capital on the farm. 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 biophysical model estimates both w_T and N_t:

$$w_T = \int_0^T \rho_t\{\mathbf{u},t\} G_t\{\mathbf{u},t\} dt \tag{5}$$

$$N_t = \frac{N_0 e^{-\mu t}}{K_t} \tag{6}$$

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. 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.

Hean and Cacho (2002, under review b) describe the bioeconomic model in detail, with particular emphasis on the economic model. Hean and Cacho (under review a) describe the growth component of the biophysical model.

Model Implementation

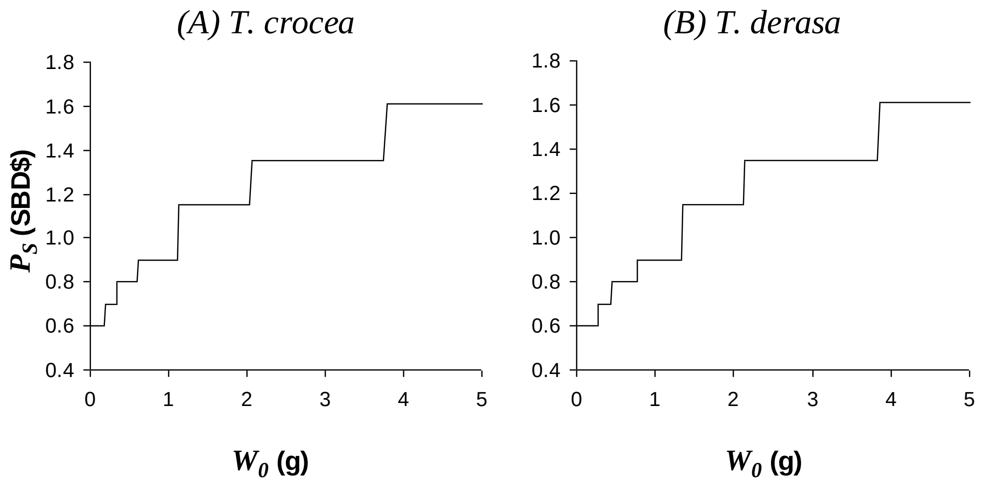
The model was implemented for *T. crocea* and *T. derasa*, using the base-case parameter values in Table 1 and price functions for clam seed and marketable clams in Figures 4 and 5 respectively. Hean and Cacho (2002, under review a, b) discuss parameter estimation using data from ICLARM's village-farming trials in Solomon Islands

All decision variables were maintained at their base-case values, and the model was solved 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. A discount rate (r) of 6 percent was assumed throughout. Mortality was initially assumed to be zero for both species; the mortality rates presented in Table 1 were then applied.

A 3×4 factorial design with four levels of *POC* (0.1, 0.2, 0.3, 0.4) and three levels of *Z* (6, 10, 14.18) was used. The base-case value for *POC* (0.2 mg C/ℓ) 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.). The base-case value for *Z* (14.18 m) was the mean of pooled data from ICLARM's *T. crocea* and *T. derasa* trials.

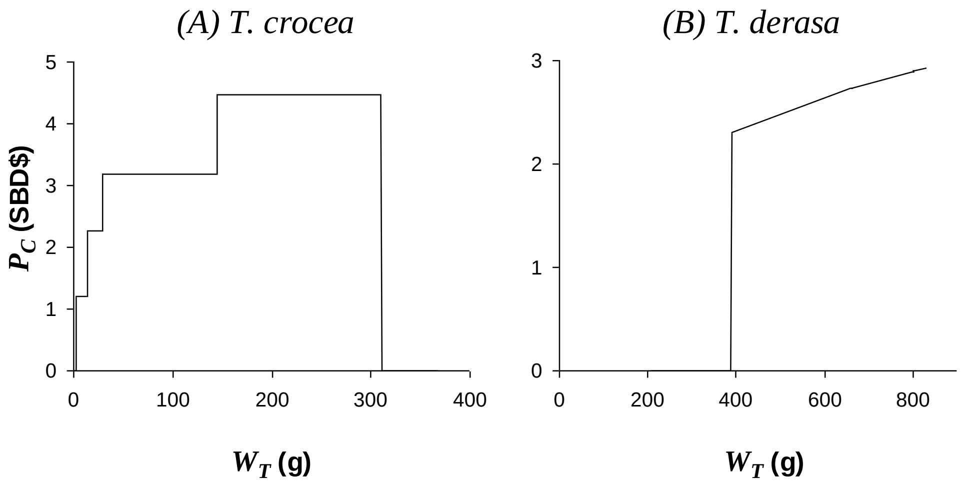
Table 1. Base-case parameter and variable values

Parameters	Value		Units
Economic:			
H	5		–
TF	26		weeks
P_L	1.50		SBD$/hr
P_K	43.38		SBD$/unit
P_M	0.95		SBD$/kg
r	0.06		–
Biological:			
N_0	200		clam seed/cage
	T. crocea	*T. derasa*	
w_0	1.313×10^{-3}	1.245×10^{-3}	kg wet weight
μ	0.0019	0.00011	clams/cage/day


(A) T. crocea

(B) T. derasa

Figure 4. Step-price functions for clam seed


(A) T. crocea

(B) T. derasa

Figure 5. Price functions for marketable clams

Results

The results of simulation modelling under optimal management are presented in Tables 2 and 3. Results are presented for optimal cycle-length (T^*), present values of profit (π^*), labour usage (L^*), total clam harvest (h^*) and the shell length of the clams at harvest (SL^*).

It is clear that profit is positively correlated with both *POC* and *Z*, and that this correlation is substantial. This is illustrated for both *T. crocea* and *T. derasa*, with no mortality, in Figure 6. For the base-case values of *POC* and *Z* (0.2 mg C/ℓ and 14.18 m), profit under optimal management is SBD$32,068 for *T. crocea* and SBD$9,261 for *T. derasa* (see Tables 2 and 3). Results indicate that, if *Z* were to fall to 6 m, a *T. crocea* farmer would need *POC* to increase by 0.15 mg C/ℓ to maintain the same profit, while a *T. derasa* farmer would need it to increase by less than 0.05 mg C/ℓ. If *POC* were to increase to 0.4 mg C/ℓ, *Z* could fall below 6 m and both farmers would still be better off than in the base case.

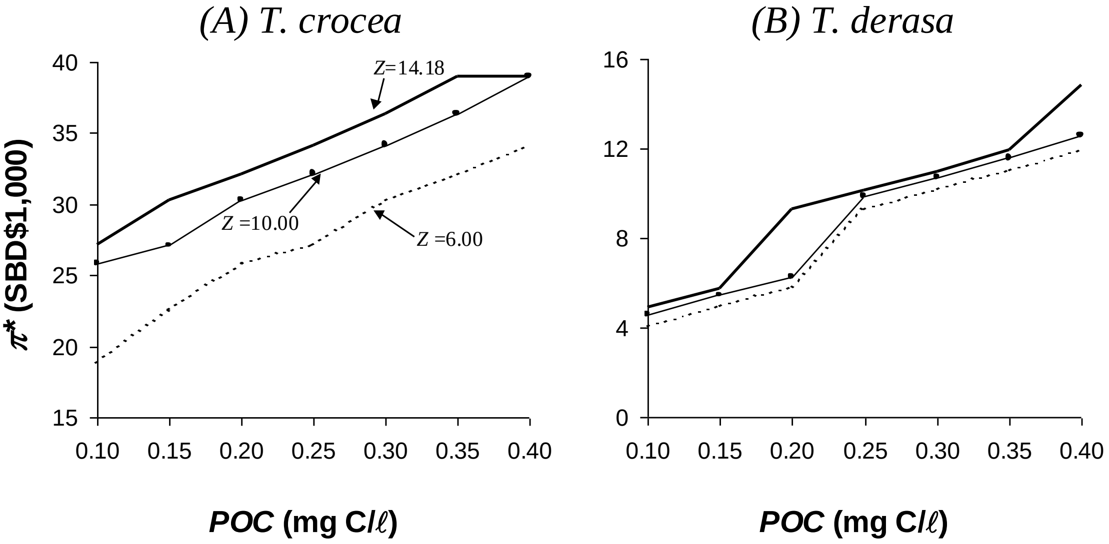


Figure 6. Maximum profit (π^*) for zero mortality

Results differ between zero- and positive-mortality only in a few cases. For *T. crocea*, they differ when *POC* is 0.1 mg C/ℓ and *Z* is 6 m and the optimal-cycle length is longest (0.52 years). π^*, L^* and h^* are SBD$18,891, 30.5 hr/cage/year and 0.59 kg respectively in the zero-mortality case, and SBD$10,107, 26.3 hr/cage/year and 0.42 kg respectively in the positive-mortality case (Table 2). For this combination of *POC* and *Z*, mortality over the cycle period reduces the number of clams at harvest, and harvest, labour and profits are lower. For *T. derasa*, π^*, L^* and h^* differ for all the combinations of *POC* and *Z* (Table 3). On average, T^* is six times longer for *T. derasa* than it is for *T. crocea* and mortality over a longer cycle period has a more significant effect. Mortality does not affect T^* or SL^* for any combination of *POC* and *Z*.

Table 2. Optimal results for *T. crocea*

	Zero mortality			Positive mortality		
POC	(Z, m)			(Z, m)		
(mg C/ ℓ)	6	10	14.18	6	10	14.18
	T^* (years)			T^* (years)		
0.1	0.52	0.40	0.38	0.52	0.40	0.38
0.2	0.40	0.35	0.33	0.40	0.35	0.33
0.3	0.35	0.31	0.29	0.35	0.31	0.29
0.4	0.31	0.27	0.27	0.31	0.27	0.27
	π^* (SBD$)			π^* (SBD$)		
0.1	18891	25876	27192	10107	25876	27192
0.2	25876	30262	32068	25876	30262	32068
0.3	30262	34100	36403	30262	34100	36403
0.4	34100	39035	39034	34100	39035	39034
	L^* (hr/cage/year)			L^* (hr/cage/year)		
0.1	30.5	31.3	32.6	26.3	31.3	32.6
0.2	31.3	35.6	37.4	31.3	35.6	37.4
0.3	35.6	39.4	41.7	35.6	39.4	41.7
0.4	39.4	44.3	44.3	39.4	44.3	44.3
	h^* (kg)			h^* (kg)		
0.1	0.59	0.58	0.59	0.42	0.58	0.59
0.2	0.58	0.59	0.59	0.58	0.59	0.59
0.3	0.59	0.60	0.59	0.59	0.60	0.59
0.4	0.60	0.59	0.62	0.60	0.59	0.62
	SL^* (cm)			SL^* (cm)		
0.1	2.56	2.54	2.56	2.56	2.54	2.56
0.2	2.54	2.55	2.55	2.54	2.55	2.55
0.3	2.55	2.57	2.56	2.55	2.57	2.56
0.4	2.56	2.56	2.58	2.56	2.56	2.58

Table 3. Optimal results for *T. derasa*

	Zero mortality			Positive mortality		
POC	(*Z*, m)			(*Z*, m)		
(mg C/ℓ)	6	10	14.18	6	10	14.18
	T^* (years)			T^* (years)		
0.1	2.74	2.51	2.42	2.74	2.51	2.42
0.2	2.15	2.03	1.98	2.15	2.03	1.98
0.3	1.82	1.75	1.71	1.82	1.75	1.71
0.4	1.59	1.52	1.48	1.59	1.52	1.48
	π^* (SBD$)			π^* (SBD$)		
0.1	4035	4606	4887	3490	3996	4245
0.2	5776	6266	9261	5034	5470	8445
0.3	10175	10738	10997	9286	9805	10042
0.4	11938	12598	14816	10909	11516	14069
	L^* (hr/cage/year)			L^* (hr/cage/year)		
0.1	44.4	40.9	39.2	42.7	39.4	37.9
0.2	33.7	30.8	28.5	32.8	30.2	28.2
0.3	27.3	26.7	26.4	27.0	26.4	26.0
0.4	25.3	24.4	22.6	24.9	24.0	22.3
	h^* (kg)			h^* (kg)		
0.1	76.28	76.12	76.27	70.41	70.26	70.40
0.2	76.05	76.64	75.99	70.20	70.74	71.56
0.3	76.06	76.84	76.55	71.63	72.36	72.09
0.4	77.04	76.70	75.91	72.55	72.23	72.94
	SL^* (cm)			SL^* (cm)		
0.1	15.02	15.01	15.02	15.02	15.01	15.02
0.2	15.01	15.04	15.01	15.01	15.04	15.01
0.3	15.01	15.05	15.04	15.01	15.05	15.04
0.4	15.07	15.05	15.00	15.07	15.05	15.00

Profit for each combination of *POC* and *Z* in Tables 2 and 3 corresponds to a different cycle-length. This is illustrated for both *T. crocea* and *T. derasa*, with no mortality, in Figure 7. For a given combination of *POC* and *Z* in Figure 7, harvesting clams at T^* years results in π^* in Figure 6. For the base-case values of *POC* and *Z* (0.2 mg C/ℓ and 14.18 m), T^* is 0.33 years for *T. crocea* and 1.98 years for *T. derasa*. The maximum profit obtained from each management strategy is SBD$32,068 and SBD$9,261 respectively, as discussed above.

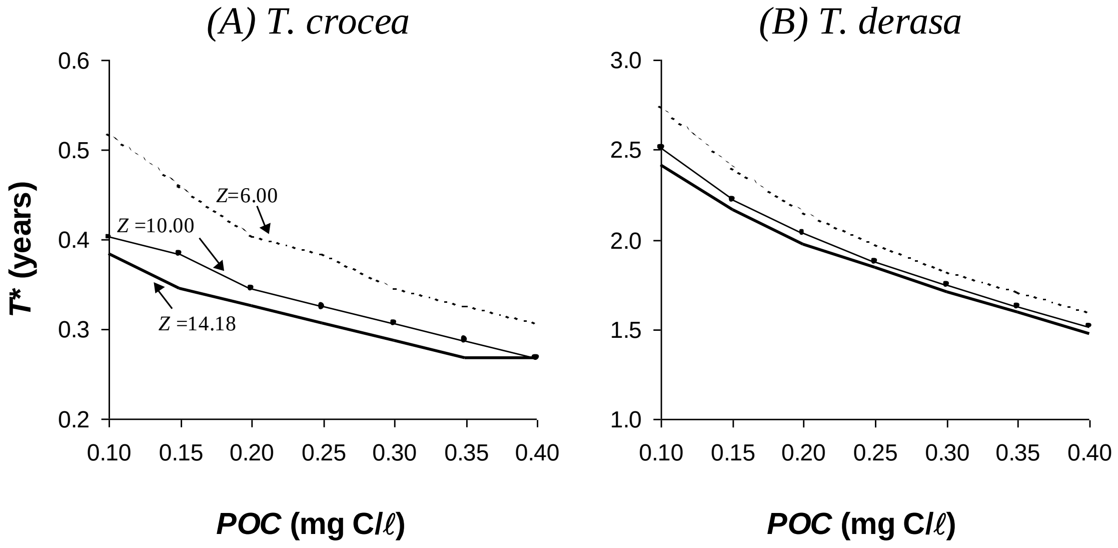


Figure 7. Optimal cycle-length (T^*) for zero mortality

Optimal cycle-length is negatively correlated with both *POC* and *Z* (Figure 7). At *POC* of 0.2 mg C/ℓ, if *Z* were to fall to 6 m, it would be optimal to harvest after a longer cycle period (0.40 years for *T. crocea* and 2.15 years for *T. derasa*). The maximum profits for these management strategies would be lower than in the base case (SBD$25,876 and SBD$5,776 respectively). At *Z* of 14.18 m, if *POC* were to increase to 0.4 mg C/ℓ, T^* would be shorter than in the base case (0.27 years for *T. crocea* and 1.48 years for *T. derasa*) and π^* would be higher (SBD$39,034 and SBD$14,816 respectively). SL^* is fairly constant for all management strategies, as both species are harvested soon after they reach their marketable shell length (2.54 cm for *T. crocea* and 15 cm for *T. derasa*).

Sensitivity analysis

When incorporated into sensitivity analysis, model results were found to be insensitive to changes in the values of a range of economic and biophysical parameters. As discussed by Hean and Cacho (2002, under review b), this is possibly because the price of marketable clams is so high relative to the cost of inputs in production. 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 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. Hean and Cacho (2002, under review b) detail the techniques used for sensitivity analysis and the problems encountered.

Value of externalities

Profit is positively correlated with both *POC* and *Z*, as discussed above. Land-based activities such as forestry that increase the nutrient concentration and turbidity of seawater in which giant clams are farmed may therefore result in externalities. In the analysis above, increasing nutrient concentration, which increases *POC*, provides village farmers with an external benefit (higher profit). In contrast, increasing turbidity, which decreases *Z*, imposes an external cost on village farmers in the form of lost profit. The value of these externalities was estimated from the profit gained or lost by giant-clam farmers due to sedimentation.

The marginal benefit of the nutrient externality is presented in Table 4. The values in the tables are the profits gained per seeded cage of giant clams for each μg increase in C/ℓ. When nutrients are low (ie. when *POC* is low, between 0.1 to 0.2 mg C/ℓ), each μg increase in C/ℓ benefits the *T. crocea* farmer by an average of SBD$59 in the zero-mortality case and SBD$103 in the positive-mortality case. When nutrients are high (ie. when *POC* is high, between 0.3 to 0.4 mg C/ℓ), the benefit is lower (SBD$32). This illustrates that the marginal benefit of nutrient leaching is higher when the water is nutrient limited. In the zero- and positive-mortality cases, the *T. derasa* farmer gains SBD$31 and SBD$39 respectively when *POC* is low, and SBD$28 when *POC* is high.

These results suggest that nutrient leaching due to land-based activities such as forestry may benefit village farmers significantly. Unfortunately, sedimentation is unlikely to affect only *POC*. Any increase in *POC* would likely be accompanied by a decrease in *Z* as discussed earlier, and the benefit from nutrient leaching may be outweighed by the cost of turbidity.

Table 4. The marginal benefit of the nutrient externality

	Marginal benefit per cage seeded (SBD$/μg C/ℓ)					
	Zero mortality			Positive mortality		
	Z (m)			*Z* (m)		
POC (mg C/ℓ)	Low	High	Mean	Low	High	Mean
	T. crocea					
Low	70	49	59	158	49	103
Med	44	43	44	44	43	44
High	38	26	32	38	26	32
Mean	51	39		80	39	
	T. derasa					
Low	17	44	31	15	42	29
Med	44	17	31	43	16	29
High	18	38	28	16	40	28
Mean	26	33		25	33	

The marginal cost of the turbidity externality is presented in Table 5. The values in the tables are the profits lost per seeded cage of giant clams for each metre of visibility lost. When turbidity is high (ie. when *Z* is low, between 6 to 10 m), each metre of visibility lost costs the *T. crocea* farmer an average of SBD$1,259 in the zero-mortality case and SBD$1,808 in the positive-mortality case, in present value terms. When turbidity is low (ie. when *Z* is high, between 10 to 14.18m), the cost is lower (SBD$324). This result was expected and illustrates that the marginal cost of turbidity is lower when the seawater is less turbid. This relationship holds at every level of *POC* considered.

In the zero- and positive-mortality cases, the *T. derasa* farmer loses an average of SBD$143 and SBD$129 respectively when *Z* is low, and SBD$344 and SBD$360 respectively when *Z* is high. This result was not expected; it indicates that the marginal cost of turbidity is lower when the seawater is more turbid.

This result is due to a sudden and significant increase in profits for this species, for 26-weekly thinning with high visibility. This spike in profits is due to the clams reaching marketable size one week prior to the next thinning. When the clams reach marketable size, there is a significant increase in revenues, and a corresponding increase in profits, followed a week later by a substantial increase in costs due to thinning and a corresponding decrease in profits. Hean and Cacho (2002, under review b) discuss this more fully. When visibility is low this opportunity is not present and there is no spike in profits, hence the marginal cost of turbidity is lower and contrary to what is expected. This suggests that thinning may have been better modelled based on some measure of “crowdedness” in the cages rather than on time. For example, thinning could be triggered once clams occupy a certain proportion of the cage area. Spikes in profit would have been avoided by modelling thinning in this way.

Table 5. The marginal cost of the turbidity externality

	Marginal cost per cage seeded (SBD$/m)					
	Zero mortality			Positive mortality		
POC	*Z* (m)			*Z* (m)		
(mg C/ℓ)	Low	High	Mean	Low	High	Mean
	T. crocea					
0.1	1746	315	1030	3942	315	2129
0.2	1097	432	764	1097	432	764
0.3	959	551	755	959	551	755
0.4	1234	0	617	1234	0	617
Mean	1259	324		1808	324	
	T. derasa					
0.1	143	67	105	127	60	93
0.2	123	716	419	109	712	410
0.3	141	62	101	130	57	93
0.4	165	530	348	152	611	381
Mean	143	344		129	360	

Clearly, the results of simulation modelling indicate that for *T. crocea* an increase in water turbidity due to land-based activities such as forestry imposes an external cost on village farmers. The true value of the turbidity externality may be underestimated here, since the calculation only takes the effect of turbidity on village-farmer profits into account and may ignore many other effects. The unexpected result for *T. derasa* may be an aberration attributable to the way in which thinning has been modelled in this paper.

Conclusions

This paper presents an illustration of how a bioeconomic model of giant-clam mariculture can be used to evaluate the value of possible externalities imposed by forestry through nutrient enrichment and turbidity of the seawater in which the giant clams are farmed. Limitations in existing scientific information may obviate the value of the model for predictive purposes. The analysis presented here demonstrates how the model can be applied when more substantial information becomes available; this is a valuable contribution. Additional information will be necessary to apply the model in actual management, particularly regarding the relationship between nutrient enrichment and turbidity for the types of sediments expected of forestry operations in Solomon Islands. Another question not explored here is the timing and duration of sedimentation.

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