

9. Model application to an externality

In this chapter, the bioeconomic model developed in Chapter 5 is used to explore the possible impact of sediment discharges in seawater on optimal management of the giant-clam operation. This is of economic interest due to the rapid expansion of the forestry industry in Solomon Islands, and the potential for aquaculture to become an important source of cash income for village communities. Land-based activities, such as forestry, may result in externalities through sediment run-off that increases the turbidity and nutrient concentration of seawater in which giant clams are farmed. The sensitivity of optimal management to changes in economic parameters is briefly discussed, and the value of sedimentation is estimated for different sediment loads.

9.1 Background to the sediment problem

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 aquaculture. This is depicted in Figure 9.1.

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. Aquaculture 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.

Forestry and agriculture are a significant threat to fisheries and aquaculture 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 aquaculture if access is unrestricted and the resource is ill treated.

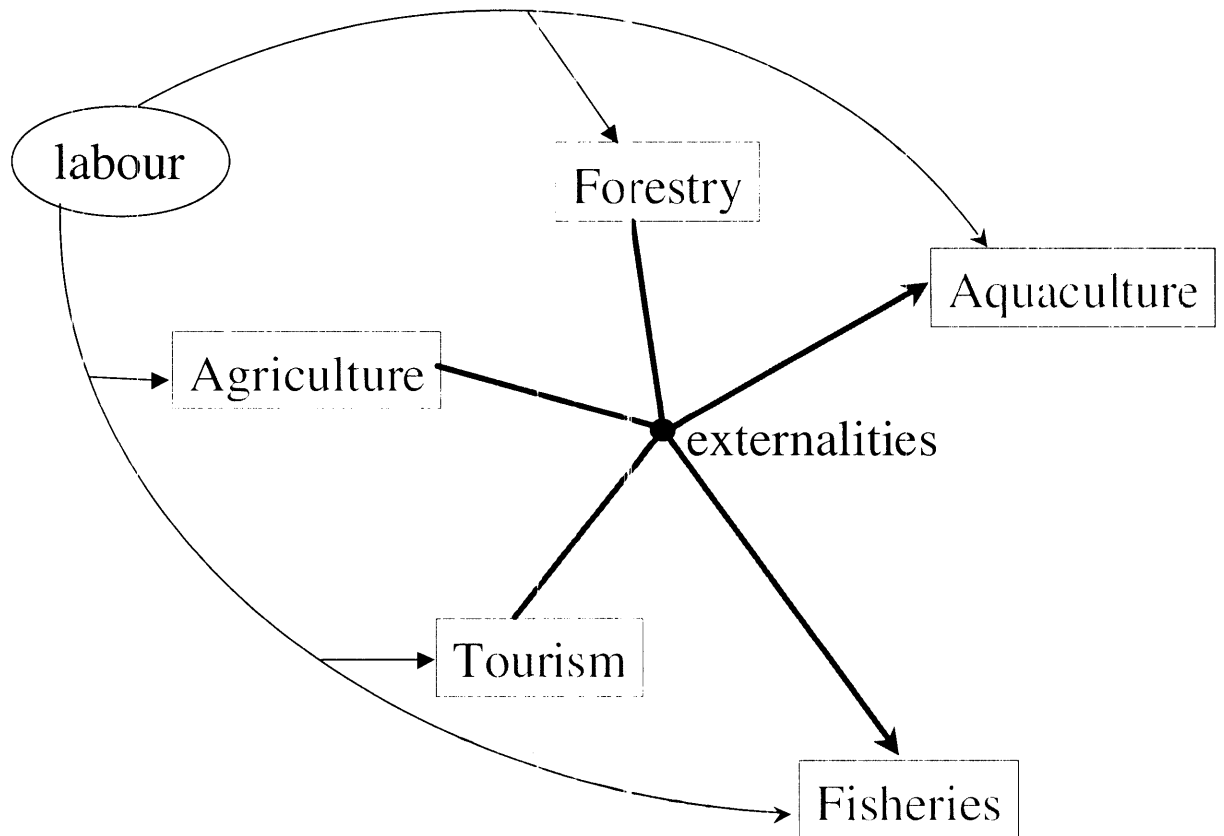


Figure 9.1. The big picture

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 chapter only the forestry externality on aquaculture 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 turbidity and nutrient leaching. 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 giant clams reared in turbid seawater have poor growth and survival (Belda *et al.*, 1988; Gomez and Belda, 1988). Nutrients have also been found to enhance clam growth and survival (Hawkins and Klumpp, 1995; Solis *et al.*, 1988). In the following analysis, the possible impact on optimal management of giant-clam farming of seawater turbidity and nutrient deposition caused by sediment run-off from forestry operations is investigated.

9.2 The sediment problem

The sediment problem involves a complex array of effects. A simplified representation of the problem is presented in Figure 9.2. 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.

In Figure 9.2, sediment can affect giant-clam production in two ways, through the particulate organic carbon content of the seawater (POC , $\text{mg C}/\ell$) and the turbidity of the seawater (measured in terms of Secchi disk visibility, V_{SD} , m). POC affects the energy intake of the clam from filter-feeding (see equation (5.27)) and V_{SD} affects the light reaching the clam for photosynthesis (see equations (5.46) to (5.47)).

Sediment from land-based activities such as forestry may be organic or inorganic. Organic sediment may affect both POC and V_{SD} . 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 V_{SD} . Some inorganic sediment (such as silt, sand and clay) may have no nutritional value and may only affect V_{SD} . Sediment may

therefore have a positive or negative effect on the metabolic processes of photosynthesis and filter-feeding depending on its composition.

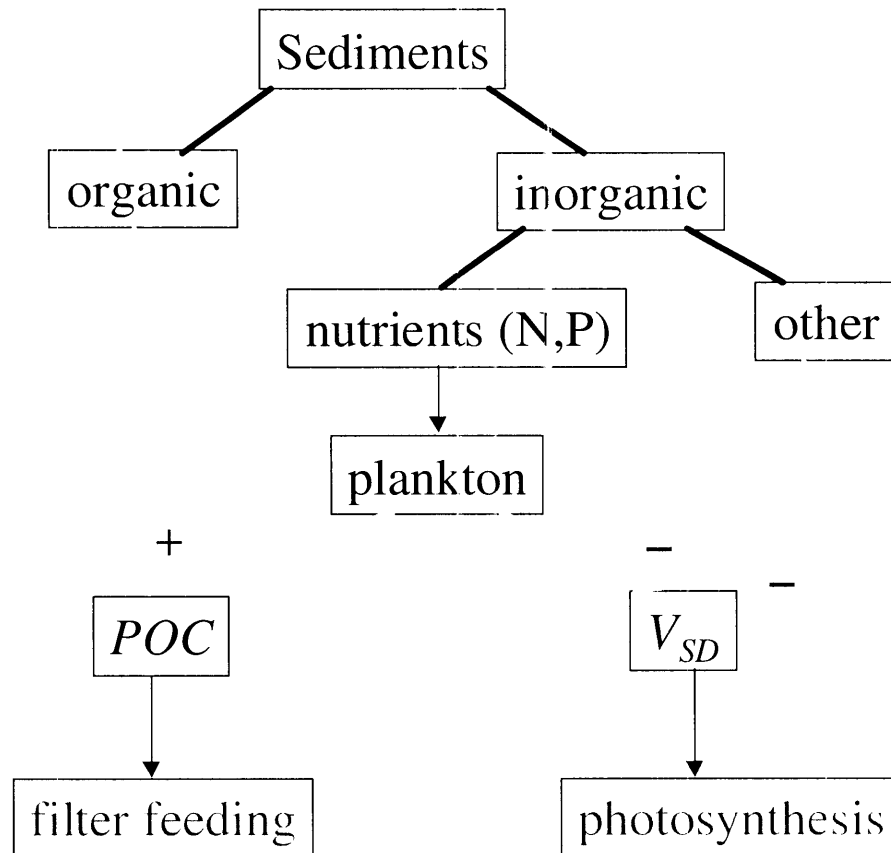


Figure 9.2. The sediment problem

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 V_{SD} ;
- the effect of nutrients on plankton blooms; and
- the effect of silt on V_{SD} .

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.

9.3 Model Implementation

The model was implemented for both *T. crocea* and *T. derasa*. Base-case parameter values and other assumptions were as presented in Tables 6.13 and 7.1. Price functions for clam seed and marketable clams were as presented in Figures 6.1 and 6.2 respectively. Mortality was initially assumed to be zero for both species, the mortality rates presented in Table 6.13 were then applied.

The model was solved for the infinite-time horizon problem, by maximising the objective function given by equation (8.1) with respect to T (harvest time):

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

Recall that h_T is total clam harvest (kg) at time T , and \mathbf{u} and \mathbf{p} are vectors of decision variables and prices respectively.

In the analysis, w_0 (initial weight) and N_0 (initial number of clam seeds) were maintained constant at their base-case values (see Table 6.13), and the model was solved for ideal management, consisting of excellent husbandry ($H=5$) and frequent thinning ($TF=26$). The model was solved over a period of five years for *T. crocea* and 15 years for *T. derasa* as was the case in Chapter 8. A 3×4 factorial design with three levels of V_{SD} (6, 10, 14.18) and four levels of POC (0.1, 0.2, 0.3, 0.4) was used. The base-case values for V_{SD} and POC used in previous chapters were 14.18 m and 0.2 mg C/ℓ respectively (Table 6.13).

9.4 Optimal management

The results of simulation modelling under optimal management are presented in look-up tables for the selected combinations of V_{SD} and POC for *T. crocea* and *T. derasa* with zero mortality (Tables 9.1 and 9.2 respectively) and for positive mortality (Tables 9.3 and 9.4 respectively). 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 V_{SD} and POC , and that this correlation is substantial. This is illustrated for both *T. crocea* and *T. derasa*, with no mortality, in Figure 9.3. For the base-case values of V_{SD} and POC (14.18 m and 0.2 mg C/ℓ), profit under optimal management is SBD\$32,068 for *T. crocea* and SBD\$9,261 for *T. derasa* (see Tables 9.1 and 9.2). Results indicate that, if V_{SD} 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, V_{SD} could fall below 6 m and both farmers would still be better off than in the base case.

Table 9.1. Optimal results for *T. crocea*, under different environmental conditions, with zero mortality

| <i>POC</i> (mg C/l) | <i>(V_{SD}</i> , m) | | |
|------------------------|--|-------|-------|
| | 6 | 10 | 14.18 |
| | Optimal cycle-length (<i>T</i> [*] , years) | | |
| 0.1 | 0.52 | 0.40 | 0.38 |
| 0.2 | 0.40 | 0.35 | 0.33 |
| 0.3 | 0.35 | 0.31 | 0.29 |
| 0.4 | 0.31 | 0.27 | 0.27 |
| | Maximum discounted profits (π^* , SBD\$) | | |
| 0.1 | 18891 | 25876 | 27192 |
| 0.2 | 25876 | 30262 | 32068 |
| 0.3 | 30262 | 34100 | 36403 |
| 0.4 | 34100 | 39035 | 39034 |
| | Optimal labour usage (<i>L</i> [*] , hr/cage/year) | | |
| 0.1 | 30.5 | 31.3 | 32.6 |
| 0.2 | 31.3 | 35.6 | 37.4 |
| 0.3 | 35.6 | 39.4 | 41.7 |
| 0.4 | 39.4 | 44.3 | 44.3 |
| | Harvest (<i>h</i> [*] , kg) | | |
| 0.1 | 0.59 | 0.58 | 0.59 |
| 0.2 | 0.58 | 0.59 | 0.59 |
| 0.3 | 0.59 | 0.60 | 0.59 |
| 0.4 | 0.60 | 0.59 | 0.62 |
| | Shell length (<i>SL</i> [*] , cm) | | |
| 0.1 | 2.56 | 2.54 | 2.56 |
| 0.2 | 2.54 | 2.55 | 2.55 |
| 0.3 | 2.55 | 2.57 | 2.56 |
| 0.4 | 2.56 | 2.56 | 2.58 |

Table 9.2. Optimal results for *T. derasa*, under different environmental conditions, with zero mortality

| <i>POC</i> (mg C/l) | <i>V_{SD}</i> , m) | | |
|------------------------|---|-------|-------|
| | 6 | 10 | 14.18 |
| | Optimal cycle-length (T^* , years) | | |
| 0.1 | 2.74 | 2.51 | 2.42 |
| 0.2 | 2.15 | 2.03 | 1.98 |
| 0.3 | 1.82 | 1.75 | 1.71 |
| 0.4 | 1.59 | 1.52 | 1.48 |
| | Maximum discounted profits (π^* , SBD\$) | | |
| 0.1 | 4035 | 4606 | 4887 |
| 0.2 | 5776 | 6266 | 9261 |
| 0.3 | 10175 | 10738 | 10997 |
| 0.4 | 11938 | 12598 | 14816 |
| | Optimal labour usage (L^* , hr/cage/year) | | |
| 0.1 | 44.4 | 40.9 | 39.2 |
| 0.2 | 33.7 | 30.8 | 28.5 |
| 0.3 | 27.3 | 26.7 | 26.4 |
| 0.4 | 25.3 | 24.4 | 22.6 |
| | Harvest (h^* , kg) | | |
| 0.1 | 76.28 | 76.12 | 76.27 |
| 0.2 | 76.05 | 76.64 | 75.99 |
| 0.3 | 76.06 | 76.84 | 76.55 |
| 0.4 | 77.04 | 76.70 | 75.91 |
| | Shell length (SL^* , cm) | | |
| 0.1 | 15.02 | 15.01 | 15.02 |
| 0.2 | 15.01 | 15.04 | 15.01 |
| 0.3 | 15.01 | 15.05 | 15.04 |
| 0.4 | 15.07 | 15.05 | 15.00 |

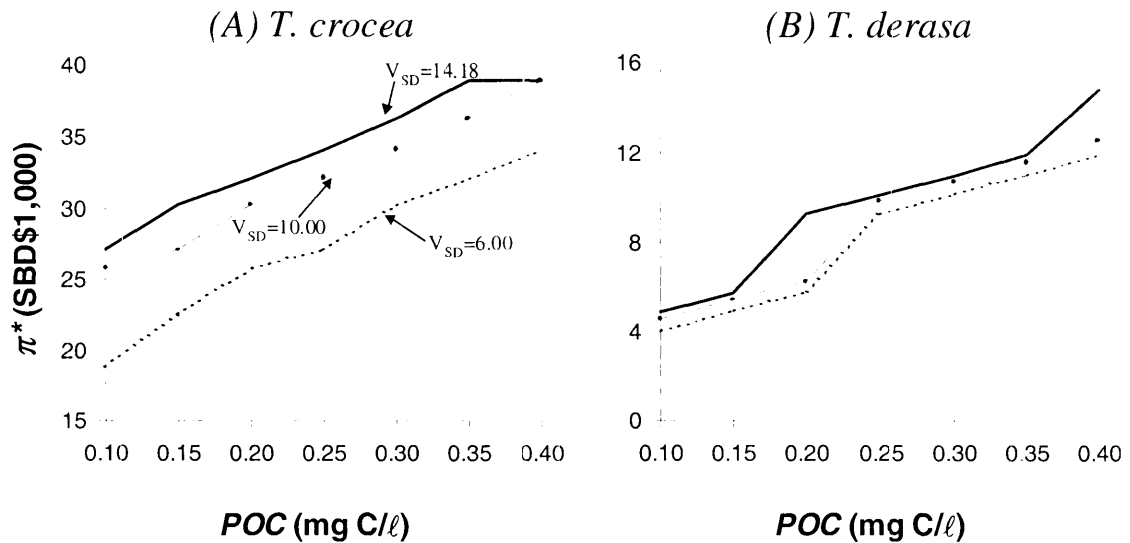


Figure 9.3. Maximum profit (π^*) for both species, under different environmental conditions, with zero mortality

Results differ between zero- and positive-mortality only in a few cases. For *T. crocea*, they differ when V_{SD} is 6 m and POC is 0.1 mg C/l, 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 (Table 9.1), and SBD\$10,107, 26.3 hr/cage/year and 0.42 kg respectively in the positive-mortality case (Table 9.3). For this combination of V_{SD} and POC, 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 V_{SD} and POC (compare Tables 9.2 and 9.4). 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 V_{SD} and POC.

Profit for each combination of V_{SD} and POC in Tables 9.1 to 9.4 corresponds to a different cycle-length. This is illustrated for both *T. crocea* and *T. derasa*, with no mortality, in Figure 9.4. For a given combination of V_{SD} and POC in Figure 9.4, harvesting clams at T^* years results in π^* in Figure 9.3. For the base-case values of V_{SD} and POC (14.18 m and 0.2 mg C/l), 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.

Table 9.3. Optimal results for *T. crocea*, under different environmental conditions, with positive mortality

| <i>POC</i> (mg C/ ℓ) | <i>(V_{SD}, m)</i> | | |
|-------------------------------|---|-------|-------|
| | 6 | 10 | 14.18 |
| | Optimal cycle-length (T^* , years) | | |
| 0.1 | 0.52 | 0.40 | 0.38 |
| 0.2 | 0.40 | 0.35 | 0.33 |
| 0.3 | 0.35 | 0.31 | 0.29 |
| 0.4 | 0.31 | 0.27 | 0.27 |
| | Maximum discounted profits (π^* , SBD\$) | | |
| 0.1 | 10107 | 25876 | 27192 |
| 0.2 | 25876 | 30262 | 32068 |
| 0.3 | 30262 | 34100 | 36403 |
| 0.4 | 34100 | 39035 | 39034 |
| | Optimal labour usage (L^* , hr/cage/year) | | |
| 0.1 | 26.3 | 31.3 | 32.6 |
| 0.2 | 31.3 | 35.6 | 37.4 |
| 0.3 | 35.6 | 39.4 | 41.7 |
| 0.4 | 39.4 | 44.3 | 44.3 |
| | Harvest (h^* , kg) | | |
| 0.1 | 0.42 | 0.58 | 0.59 |
| 0.2 | 0.58 | 0.59 | 0.59 |
| 0.3 | 0.59 | 0.60 | 0.59 |
| 0.4 | 0.60 | 0.59 | 0.62 |
| | Shell length (SL^* , cm) | | |
| 0.1 | 2.56 | 2.54 | 2.56 |
| 0.2 | 2.54 | 2.55 | 2.55 |
| 0.3 | 2.55 | 2.57 | 2.56 |
| 0.4 | 2.56 | 2.56 | 2.58 |

Table 9.4. Optimal results for *T. derasa*, under different environmental conditions, with positive mortality

| <i>POC</i> (mg C/l) | <i>(V_{SD}</i> , m) | | |
|------------------------|--|-------|-------|
| | 6 | 10 | 14.18 |
| | Optimal cycle-length (<i>T</i> [*] , years) | | |
| 0.1 | 2.74 | 2.51 | 2.42 |
| 0.2 | 2.15 | 2.03 | 1.98 |
| 0.3 | 1.82 | 1.75 | 1.71 |
| 0.4 | 1.59 | 1.52 | 1.48 |
| | Maximum discounted profits (π^* , SBDS\$) | | |
| 0.1 | 3490 | 3996 | 4245 |
| 0.2 | 5034 | 5470 | 8445 |
| 0.3 | 9286 | 9805 | 10042 |
| 0.4 | 10909 | 11516 | 14069 |
| | Optimal labour usage (<i>L</i> [*] , hr/cage/year) | | |
| 0.1 | 42.7 | 39.4 | 37.9 |
| 0.2 | 32.8 | 30.2 | 28.2 |
| 0.3 | 27.0 | 26.4 | 26.0 |
| 0.4 | 24.9 | 24.0 | 22.3 |
| | Harvest (<i>h</i> [*] , kg) | | |
| 0.1 | 70.41 | 70.26 | 70.40 |
| 0.2 | 70.20 | 70.74 | 71.56 |
| 0.3 | 71.63 | 72.36 | 72.09 |
| 0.4 | 72.55 | 72.23 | 72.94 |
| | Shell length (<i>SL</i> [*] , cm) | | |
| 0.1 | 15.02 | 15.01 | 15.02 |
| 0.2 | 15.01 | 15.04 | 15.01 |
| 0.3 | 15.01 | 15.05 | 15.04 |
| 0.4 | 15.07 | 15.05 | 15.00 |

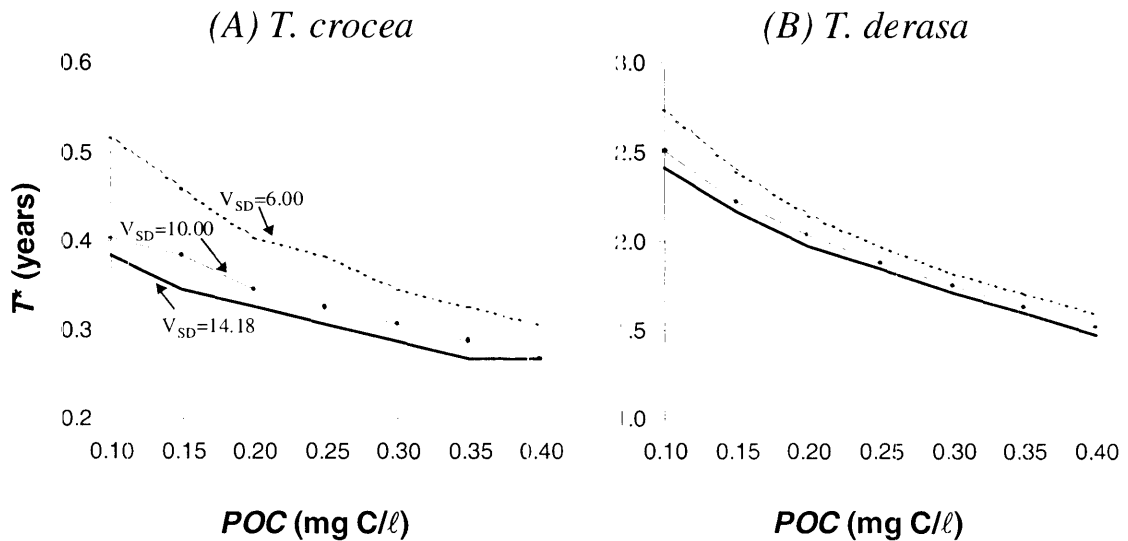


Figure 9.4. Optimal cycle-length (T^*) for both species, under different environmental conditions, with zero mortality

Optimal cycle-length is negatively correlated with both V_{SD} and POC (Figure 9.4). At POC of 0.2 mg C/l, if V_{SD} 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 V_{SD} 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*).

As in Chapter 8, sensitivity analysis was undertaken for a selection of economic and biological parameters, and as found there, the model results were insensitive to changes in parameter values.

9.5 Value of externalities

Profit is positively correlated with both V_{SD} and POC , as discussed above. Land-based activities such as forestry that increase the turbidity and nutrient concentration of

seawater in which giant clams are farmed may therefore result in externalities. In the analysis above, increasing turbidity, which decreases V_{SD} , imposes an external cost on village farmers in the form of lost profit. In contrast, increasing nutrient concentration, which increases POC , provides village farmers with an external benefit (higher profit). The value of these externalities was estimated from the profit lost or gained by giant-clam farmers due to sedimentation.

The marginal cost of the turbidity externality is presented in Table 9.5. The values in the tables are the profits lost per seeded cage of giant clams for each metre of Secchi disk visibility lost. When turbidity is high and V_{SD} 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 the turbidity of the seawater is low and V_{SD} 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 V_{SD} is low, and SBD\$344 and SBD\$360 respectively when V_{SD} is high. This result was not expected; it indicates that the marginal cost of turbidity is lower when the seawater is more turbid. It seems likely that this perverse result is due to the spike in profits noted for this species for 26-weekly thinning with high visibility in Figure 3.2. The spike in profits is due to the clams reaching marketable size only two weeks prior to the next thinning. 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. Spikes in profit would have been avoided by modelling thinning in this way.

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 perverse result for *T. derasa* may be an aberration attributable to the way in which thinning has been modelled in this study.

Table 9.5. The marginal cost of the turbidity externality for both species for the zero- and positive-mortality cases

T. crocea

| <i>POC</i> (mg C/ℓ) | Marginal cost per cage seeded (SBD\$/m) | | | | | |
|------------------------|---|---------------------------|------|--------------------|---------------------------|------|
| | Zero mortality | | | Positive mortality | | |
| | Low | <i>V_{SD}</i> (m) | | Low | <i>V_{SD}</i> (m) | |
| | | High | Mean | | High | Mean |
| 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

| <i>POC</i> (mg C/ℓ) | Marginal cost per cage seeded (SBD\$/m) | | | | | |
|------------------------|---|---------------------------|------|--------------------|---------------------------|------|
| | Zero mortality | | | Positive mortality | | |
| | Low | <i>V_{SD}</i> (m) | | Low | <i>V_{SD}</i> (m) | |
| | | High | Mean | | High | Mean |
| 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 | |

The marginal benefit of the nutrient externality is presented in Table 9.6. 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 and *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 and *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 V_{SD} (see Section 9.2) and the benefit from nutrient leaching may be outweighed by the cost of turbidity.

Table 9.6. The marginal benefit of the nutrient externality for both species for the zero- and positive-mortality cases

T. crocea

| <i>POC</i> (mg C/ℓ) | Marginal benefit per cage seeded (SBD\$/μg C/ℓ) | | | | | |
|------------------------|---|--------------|------|--------------------|--------------|------|
| | Zero mortality | | | Positive mortality | | |
| | | V_{SD} (m) | | | V_{SD} (m) | |
| | Low | High | Mean | Low | High | Mean |
| 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

| <i>POC</i> (mg C/ℓ) | Marginal benefit per cage seeded (SBD\$/μg C/ℓ) | | | | | |
|------------------------|---|--------------|------|--------------------|--------------|------|
| | Zero mortality | | | Positive mortality | | |
| | | V_{SD} (m) | | | V_{SD} (m) | |
| | Low | High | Mean | Low | High | Mean |
| 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 | |

9.6 Summary

This chapter presents an illustration of how the bioeconomic model can be used to evaluate the value of externalities imposed on giant-clam farming through seawater turbidity and nutrient deposition. 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 in itself. Additional information will

be necessary to apply the model in actual management, particularly regarding the relationship between turbidity and nutrient enrichment for the types of sediments expected of forestry operations in Solomon Islands. Another question not explored here is the timing and duration of sedimentation.

10. Conclusion

Giant clams (*Tridacnidae*) offer interesting possibilities for small holders (village farmers) in Solomon Islands. Giant clams obtain their nutrition from photosynthesis and filter-feeding, hence no feed expenses are incurred, and the capital required for their culture is low technology, consisting of wire mesh, steel rods, and a few tools for building cages and cleaning them. A lot of research funds have been invested to develop the production technology to rear seed in a hatchery and raise clams to marketable size in the ocean; ACIAR alone has invested about \$1.5M (Menz, 2000, pers. comm.). The current markets for giant clams for aquaria and as seafood are small, but the seafood market can potentially be sizeable. Given the uncertainties regarding the possible development of a stable market for giant clams, which may benefit not only Solomon Islands, but also other small Pacific Island nations, there is a need to evaluate the potential benefits from funds invested in research, extension and marketing. An attempt should be made to allocate funds as efficiently as possible. This thesis goes some way towards this goal by developing a conceptual model of the evaluation problem which has, at its core, a bioeconomic model for the potential supply of giant clams from a village farm.

In the preceding chapters, a detailed bioeconomic model was developed and applied to the development of giant-clam farming in Solomon Islands as a case study. The results of model simulations are dependent on given parameters and model assumptions, some of which are based on limited data. Also, there is uncertainty about the development of the commercial industry. Further research that improves parameter estimation will enhance the predictive ability of the bioeconomic model developed in this thesis. This chapter presents a summary of the research, identifies the major findings, and highlights further research needs.

10.1 Summary

A detailed bioeconomic model was developed comprising economic and biophysical models. The economic model describes the costs and revenues associated with

farming a giant-clam population from planting through to harvest. The biophysical model describes the average growth of an individual giant clam and survival within the population.

The growth component of the biophysical model is a dynamic simulation model consisting of a set of differential equations. The model simulates the clam's basic metabolic processes of photosynthesis, filter-feeding and respiration, as well as surplus energy demand for unaccounted metabolic processes such as reproduction. Growth is affected by environmental and management variables. An innovation in the model is its ability to simulate the effect of husbandry and thinning frequency on growth. Husbandry attenuates algal build-up in the clam's cage which reduces energy intake from photosynthesis through shading, and from filter-feeding through inhibiting water flow. Thinning mitigates crowding which reduces energy intake from photosynthesis since the clam is not able to fully project its mantle as space becomes limiting.

The survival component of the biophysical model is described by a simple decay function. This was deemed appropriate since analysis of survival data for two species of giant clam from a large number of ICLARM's village-farming trials in Solomon Islands did not provide conclusive evidence regarding the effects of environmental and management variables on mortality. Changes in the giant-clam population are attributed to mortality alone, with no account given to reproduction, since farmed clams are usually harvested prior to sexual maturity.

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 incorporates information on costs, including clam seed, labour, capital and marketing services, and revenues associated with farming a giant-clam population from planting through to harvest. The economic model is based on the economic theory of optimal forestry exploitation.

The operation of the growth model was investigated in detail for *T. crocea* and *T. derasa*. As expected, model simulations show that growth is positively correlated with husbandry and negatively correlated with the time interval between thinnings. The

effect of thinning is most evident for *T. derasa*, which grows the quicker of the two species and to a larger size. Thinning does not affect the growth of *T. crocea* unless it is very infrequent and the clams become crowded. Husbandry and thinning are substitute inputs in production, so a village farmer can produce a clam of a particular target size by substituting labour between these two activities. This has implications for the cycle-length required for the clams to reach their target size, since cycle-length is also affected by these management variables. Cycle-length is negatively correlated with husbandry and positively correlated with the time interval between thinnings, except for *T. crocea* for which thinning frequency has no effect.

In the model, the combination of husbandry, thinning frequency and cycle-length determines the amount of labour and capital used in production. One difficulty for this research was establishing the relationships between these variables. Both husbandry and thinning are activities requiring labour; thinning also affects the amount of capital used on the farm. Husbandry and thinning affect the optimal cycle-length, through their influence on clam growth (and therefore revenue) and the cost of production inputs. Cycle-length in turn affects the amount of labour and capital used, because it sets the period over which husbandry and thinning are undertaken. Modelling these relationships was a major challenge of the research. They had not been modelled previously and this represents a major contribution of this study.

The bioeconomic model is used in a normative analysis to explore optimal management of the giant-clam operation for *T. crocea* and *T. derasa*, farmed for the aquarium and seafood markets respectively. This 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 multiple-cycle results 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 when

husbandry is very good, however the optimal cycle-length is longer (just over 2 years) and thinning is every 6 months. Thinning is necessary for optimal management of *T. derasa* due to the effects of crowding over the longer cycle period. 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 intensive. Although the opportunity cost of labour used in the model is low, as it is based on copra production which is the most likely alternative source of cash income, 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.

The optimal management results were used in a hypothetical adoption analysis. Based on conservative estimates, results suggest that potential industry supply of giant clams from Solomon Islands to the niche aquarium market may need to be curtailed by contracts limiting the number of aquarium farmers or the level of their production. Although farming clams for the aquarium market is more profitable, large-scale adoption will depend on the development of the seafood market. Assuming demand is perfectly elastic, potential industry supply to the seafood market from Solomon Islands was estimated to be 260 tonnes of live clams, or 35 tonnes of meat, after 30 years.

In addition to the application of the model to study potential supply, the model was used to investigate the possible externalities imposed by forestry on optimal management of the giant-clam operation. This simulation was undertaken due to the rapid expansion of the forestry industry in Solomon Islands, and the potential for sediment run-off from forestry to impose externalities on giant-clam farming through seawater turbidity and nutrient deposition. The effects of different combinations of water clarity and nutrient concentration were considered. The results of the simulations indicate that maximum profit is positively correlated, and optimal cycle-length is negatively correlated, with both variables. Turbidity therefore imposes an external cost on village farmers in the form of lost profits, while nutrient deposition provides an external benefit in the form of gained profits. Sedimentation that

increases nutrient deposition is likely to also increase turbidity, and the benefit of the former may be outweighed by the cost of the latter.

10.2 Major Research Needs

Results from the bioeconomic model applications are based on a particular set of parameter values in the biophysical model and assumptions about input usage and prices in the economic model. Important areas for future research are those that would enhance the predictive ability of the bioeconomic model. Ongoing research into the effect of environmental and management variables on growth and survival would be particularly useful. This would allow the biophysical model to more realistically predict giant-clam production at different locations and for different management strategies. Further research into the use and opportunity cost of inputs would help to more accurately model the costs of production, particularly labour which may be a significant constraint to adoption of the technology. Research into the factors that affect the rate of adoption, as well as the potential demand for cultured giant-clam products in both the aquarium and seafood markets, and the growth (or otherwise) of these markets, is also warranted. These factors will all affect profitability of the giant-clam operation in the long run. The adoption study could also be expanded into an industry-level evaluation to show how increasing supply would affect the overall market. This will require estimation of demand functions, and is not pursued in this study.

Additional research into the relationship between turbidity and nutrient enrichment for the types of sediments expected by forestry operations would allow more accurate predictions about the externalities imposed on giant-clam farming. It would also be valuable to investigate the extent of infrastructure deficiencies (particularly transport) and the potential for removing or lessening these constraints to the development of the emerging mariculture industry.

Specific research needs in terms of the biophysical and economic models are highlighted below.

10.2.1 Biophysical model

Parameter values used in the growth model were drawn from the scientific literature or were estimated based on biophysical processes or using experimental data. Some parameter values, which were unknown or poorly known, were calibrated using observed data from ICLARM's village-farming trials, others could not be calibrated due to data limitations and were maintained at their best-guess initial values. Growth model predictions were compared with observed data from ICLARM's village-farming trials and were found to provide a good fit over the duration of the trials. Sensitivity analysis of the growth-model parameters showed that predicted growth of both *T. crocea* and *T. derasa* is very sensitive to photosynthesis, respiration and surplus-energy-intake parameters (which regulate different metabolic processes), and the temperature-dependent respiratory-response parameters (which control how the clam's respiration responds to temperature). This means that results for giant-clam growth are very sensitive to small errors in these parameter values. Research should focus on better understanding the relationships between these parameters and clam growth.

A particularly troublesome set of parameters was for the surplus-energy-age equation, which ensures that clams do not grow beyond the maximum size for their species. The insensitivity of the growth model to these parameters is due to the short duration over which growth was simulated; their effect comes into play with older clams. In the markets analysed in this study, clams are harvested before they reach sexual maturity and hence errors in these parameter values do not have a critical effect. Model results for markets requiring a longer grow-out period would likely be more sensitive to these parameters. There is very little information available about energy expenditure on metabolic processes other than routine respiration; so further research into surplus-energy expenditure is warranted.

Other parameters to which growth model results were insensitive but which merit attention are the husbandry and density parameters. The effects of husbandry and thinning frequency on clam growth were described in the previous section; they have

not been modelled prior to this study and further work is required to build on the estimates derived here.

In the biophysical model, survival is described by a decay function with a constant mortality parameter. Although environmental conditions and management variables should affect the mortality parameter, data available did not provide any useful information on this. A better understanding of the factors affecting survival is required, since mortality can have a significant effect on the level of production.

10.2.2 Economic model

Parameter values used in the economic model are based on very limited data about input usage and costs, and uncertainty about the development of the commercial industry. Information about input usage and costs was obtained through informal interviews with ICLARM staff and village farmers, and used as a guide to determining costs for the model; more detailed measurements of these costs are needed. Analysis is also based on constant prices and no account is taken of price movements over time due to the interaction of market demand and increasing adoption of the technology. Research into potential demand in emerging markets and factors affecting adoption is worthy of attention.

Economic model results suggest that the price of seed clams is low relative to the price of marketable clams, and hence it is optimal to harvest as soon as clams reach marketable size. The cost of seed used in this study is based on estimates provided by ICLARM, whether this price will increase once production is undertaken by private firms is an empirical question that can be answered by studying the hatchery phase in more detail, using market costs for inputs, including capital.

In hindsight, a possible improvement to the model would be to make thinning dependent on some measure of cage density rather than time. For example, thinning could be triggered once clams occupy a certain proportion of the cage area. The use of thinning based on “crowdedness” rather than time, seems to be a better decision

variable. This question was not explored here because of time constraints, but it remains an important subject for future research.

Clearly, civil unrest that currently affects Solomon Islands will slow down market emergence in that country. This does not mean that the industry will fail to develop. There are good prospects for development in other Pacific Island nations with similar environmental and social conditions.

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