

7. Biophysical Simulation and Sensitivity Analysis

A detailed biophysical model describing the average growth of an individual giant clam and survival within the population was developed in Chapter 5. In this chapter, calibration and validation of the growth model is described. The sensitivity of the model to biological and environmental parameters and the effect of decision variables on growth predictions are investigated. The input substitutability between labour and time (ie. cycle-length) in the production of clams of a particular target size is investigated. The operation of the survival model is not examined since survival is described by a simple decay function (see Sections 5.2.2.2 and 6.3.3).

7.1 Model Calibration

Estimation of growth-model parameters was not a trivial process. Some parameters were reported in the scientific literature and some parameters were estimated algebraically or statistically (using a Marquardt algorithm) based on biophysical processes or using experimental data. Some parameters whose values were unknown or poorly known were estimated by fitting the model to time-series growth data collected by ICLARM for *T. crocea* and *T. derasa* from their respective village-farming trials (see Section 6.3.2). This process is known as model calibration and is described below. More details on model calibration can be found in Cacho (1997) and France and Thornley (1984).

The model was calibrated for each species by simulating the trial conditions that produced the growth data sets. ICLARM had collected time-series environmental and husbandry data which made this possible (see Section 6.3.4). The growth data was converted from shell lengths (*SL*, cm), in which it had been collected, to tissue dry weights (*TDW*, g) (see Section 6.3.2). The trace of the mean observed *TDW*s for each cage was compared with the average *TDW* predicted by the model for that cage. For each species, the known model parameters were held constant, while the unknown or

poorly known parameters were given “best-guess” initial values. The model was then run iteratively until the combination of parameter values that produced the best growth predictions was found. Model fitness was based on minimisation of the sum of squared deviations between observed and predicted *TDWs*.

The husbandry parameter, α_H , and the temperature-dependent photosynthetic response parameters, $Temp_{opt}$ and $Temp_{max}$, were calibrated in this way. α_H was selected for calibration since the effect of husbandry on energy intake had not been modelled prior to this study and is not well understood. $Temp_{opt}$ and $Temp_{max}$ were chosen for calibration because the clams in the village-farming trials were growing in water temperatures mostly within the range of the best-guess initial values for these parameters, which were 28 °C and 33 °C respectively. Had $Temp_{opt}$ and $Temp_{max}$ not been calibrated, gross algal photosynthesis would have been significantly underestimated at high temperatures (see equations (5.17) and (5.20)-(5.23)). The photosynthesis parameter, α_p , was subsequently re-estimated algebraically because it was initially based on the best-guess initial values for $Temp_{opt}$ and $Temp_{max}$.

The surplus-energy parameters, α_E , β_E , α_A and β_A , were considered for calibration, since energy expenditure on metabolic processes other than routine respiration is not well understood. However, this was not possible due to data limitations. Calibration of α_E and β_E would require time-series data for irradiance and the particulate organic carbon content of the seawater, but ICLARM did not collect this data. In the biophysical model, irradiance is given by an annual cycle (see Section 5.2.2.3) and particulate organic carbon is held constant at its base value (see Table 6.13). Calibration of α_A and β_A would require growth data close to the clams’ maturity, but ICLARM did not collect growth data after the termination of the farming trials (which ran for a maximum of two years). All four surplus-energy parameters were therefore maintained at their best-guess initial values.

The parameters that produced the best growth predictions for *T. crocea* and *T. derasa* are presented in Table 7.1. Where possible, parameters are also presented for other species. However, these parameters have not been through a calibration process.

Table 7.1. Growth model parameters

Parameter	<i>T. crocea</i>	<i>T. derasa</i>	<i>T. gigas</i>	<i>T. squamosa</i>	<i>T. tevoroa</i>	<i>H. hippopus</i>	Units	Source ^a	Equation
α_{Hi}	0.0185	0.0144	Na	Na	na	na	—	A ^b	5.15
PQ	1	1	1	1	1	1	—	F,G	5.16
RQ	0.8	0.8	0.8	0.8	0.8	0.8	—	E,F,G	5.16
k_a	0.05	0.05	0.05	0.05	0.05	0.05	—	B,E,F,G,I	5.16
TR	0.95	0.95	0.95	0.95	0.95	0.95	—	B,C,F,G	5.16
I_k	0.5040	0.2050	0.3819	0.4187	0.2105	0.5658	MJ/m ² .hr	A,F,G	5.17
α_M	16.7507	17.5318	35.6741	53.0678	na	33.2282	cm ²	A,D,F,G	5.19
β_M	0.6392	0.7777	0.7122	0.7038	na	0.6182	—	A,D,F,G	5.19
α_P	2.2186	2.1373	3.6751	1.3563	1.8876	0.4935	mg C/hr	A,F,G	5.20
β_P	0.677	0.744	0.693	0.914	0.710	1.121	—	A,F,G	5.20
Ψ_{max}	1	1	1	1	1	1	—	A	5.21
$Temp_{max}$	38.2172	38.6966	33.0000	33.0000	33.0000	33.0000	°C	A,H	5.21
$Temp_{opt}$	28.5924	29.0617	28.0000	28.0000	28.0000	28.0000	°C	A	5.21
Q_{10}	1.67	1.67	1.67	1.67	1.67	1.67	—	A,H	5.23
α_R	10.9536	18.5029	18.9943	8.7147	16.5751	1.8537	mg C/day	A,F,G	5.24
β_R	0.597	0.736	0.654	0.821	0.726	1.124	—	A,F,G	5.24
ϕ_1	0.000030591	0.000030591	0.000030591	0.000030591	0.000030591	0.000030591	—	A,H	5.25
ϕ_2	301.74	301.74	301.74	-301.74	-301.74	-301.74	—	A,H	5.25
ϕ_3	0.00071459	0.00071459	0.00071459	0.00071459	0.00071459	0.00071459	—	A,H	5.25
ϕ_4	-312.26	-312.26	-312.26	-312.26	-312.26	-312.26	—	A,H	5.25
AE	0.5540	0.5463	0.5080	0.5770	na	0.8050	—	A,E,F,G	5.26

α_F	14.0400	14.2457	88.3200	7.6320	16.6166	12.6000	ℓ /day	A,F,G	5.28
β_F	0.905	0.700	0.397	0.964	0.680	0.743	—	A,F,G	5.28
α_E	0.4915	0.2018	0.7082	0.2018	na	0.1022	mg C/day	A,F	5.31
β_E	1.0727	1.1788	0.9757	1.1788	na	1.2762	—	A,F	5.31
α_A	0.0003	0	0.00000075	0	na	0	—	A	5.32
β_A	1.5	1.5	1.5	1.5	1.5	1.5	—	A	5.32
α_C	0.8547	0.7899	0.7440	0.7899	na	0.5915	—	A,F	5.33
β_C	-0.0100	0.0058	0.0170	0.0058	na	0.0484	—	A,F	5.33
k_d	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	g TDW/mg C	A,F	5.35
α_S	18.2019	44.1172	46.2210	34.8062	na	92.1215	g SDW	A,F,G	5.36
β_S	1.0833	1.2342	0.9256	0.9644	na	0.8728	—	A,F,G	5.36
α_L	4.9510	8.4796	8.4170	7.9273	8.0908	7.6999	cm	A,F,G	5.37
β_L	0.3086	0.3506	0.2976	0.2740	0.3557	0.2890	—	A,F,G	5.37
k_w	0.1	0.1	0.1	0.1	0.1	0.1	—	A,G	5.38

na denotes parameter not available.

— denotes unitless parameter.

^a Sources: A, this study; B, Fisher *et al.*, 1985; C, Fitt, 1993b; D, Griffiths and Klumpp, 1996; E, Klumpp *et al.*, 1992; F, Klumpp and Griffiths, 1994; G, Klumpp and Lucas, 1994; H, Mingoa, 1990; I, Trench *et al.*, 1981.

^b Parameters attributed to this study were estimated algebraically or statistically based on biophysical processes or using experimental data reported in the source following. Some parameters whose values were unknown or poorly known were estimated through a calibration process. Parameter estimation and calibration are described in detail in Section 7.1.

7.2 Model Validation

Model validation involves comparing model predictions with observed data that has ideally not been previously used in parameter estimation (Cacho, 1997). For this study, insufficient data was available for both parameter estimation and independent validation. The growth model was validated by simulating the village-farming trials for *T. crocea* and *T. derasa* (as in Section 7.1) and comparing observed and predicted *TDW*s.

For *T. crocea*, the mean observed *TDW* for the 47 trial cages was 0.312 g after 10 months and 1.103 g after 22 months. Model predictions were 0.256 g and 1.005 g after 10 and 22 months respectively. For *T. derasa*, the mean observed *TDW* for the 112 trial cages was 1.743 g after 1 year and 5.192 g after 2 years. Model predictions were 1.635 g and 4.690 g after 1 and 2 years respectively.

In Figures 7.1 and 7.2 predicted *TDW* is compared with the trace of the mean observed *TDW*s for four trial cages of *T. crocea* and *T. derasa* respectively. The four cages presented for each species are from different trial sites. For the four cages of *T. crocea*, the mean observed *TDW* was 0.262 g after 10 months and 0.978 g after 22 months. Predicted *TDW*s were 0.276 g and 1.050 g after 10 and 22 months respectively. For the four cages of *T. derasa*, the mean observed *TDW* was 1.632 g after 1 year and 4.219 g after 2 years. Predicted *TDW*s were 1.737 g and 4.683 g after 1 and 2 years respectively.

7.3 Sensitivity Analysis

Sensitivity analysis was undertaken for *T. crocea* and *T. derasa* to evaluate the effect of changes in parameter values on the growth of each species. This was accomplished by changing the value of each parameter in turn, while keeping the values of all other parameters at their base values, and running the model. Interactions among parameters were not investigated although they may have important effects (Cacho, 1990, 1997).

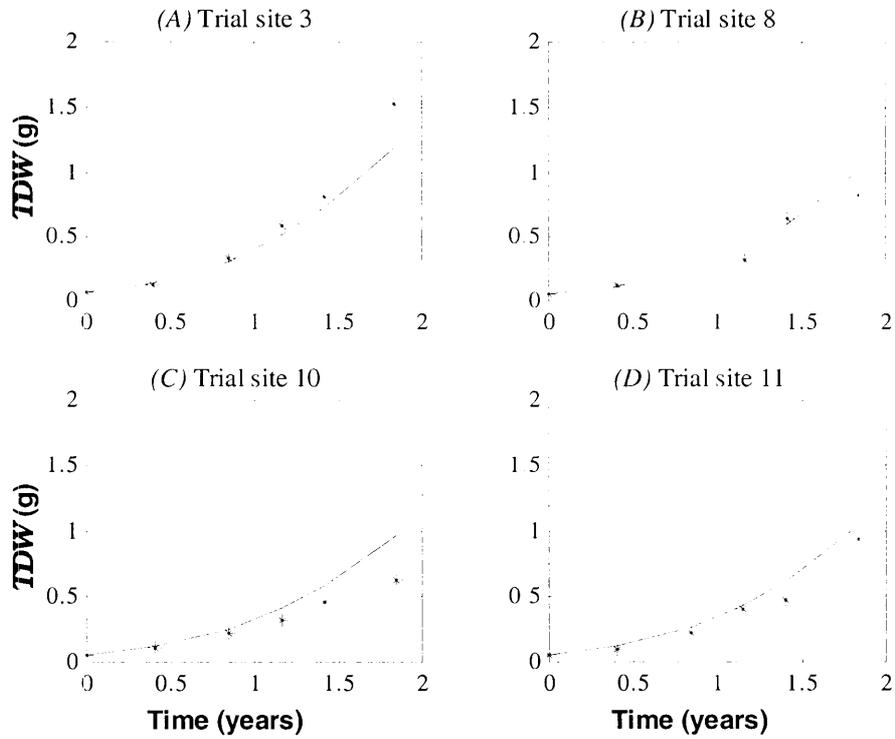


Figure 7.1. Observed (*) and predicted tissue dry weight (*TDW*) of *T. crocea* farmed at a selection of ICLARM trial sites

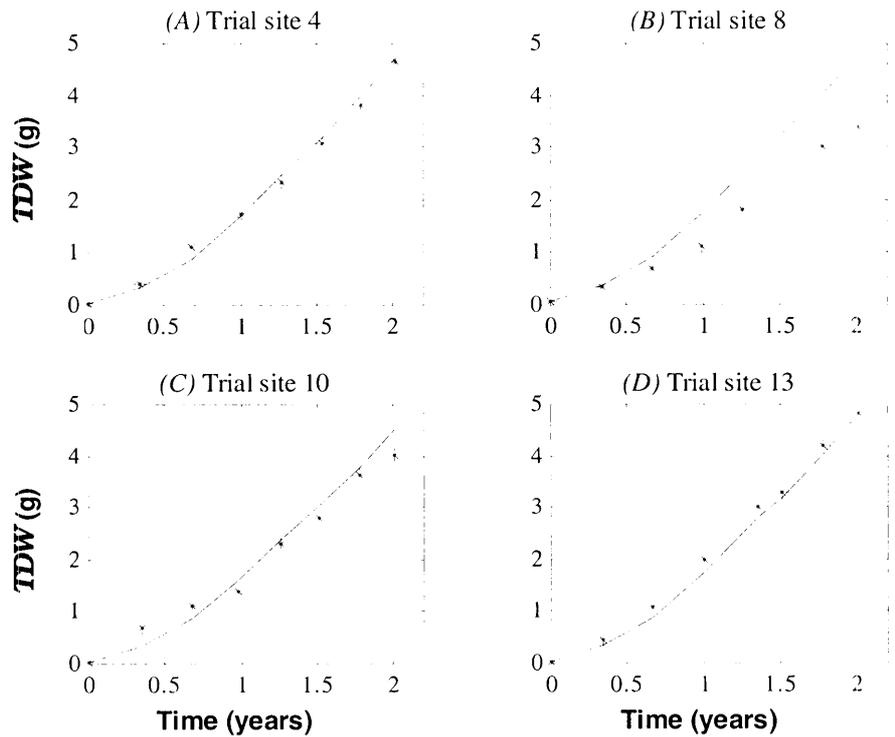


Figure 7.2. Observed (*) and predicted tissue dry weight (*TDW*) of *T. derasa* farmed at a selection of ICLARM trial sites

The model was run for 5 years under “ideal” management, consisting of excellent husbandry ($H=5$) and frequent thinning ($TF=26$) for the base-case parameters (see Table 7.1) and for parameter values one percent lower and one percent higher than the base case. Results are presented below for the base case and for groupings of biophysical and environmental parameters. The biophysical parameters regulate the clam’s metabolic processes, while the environmental parameters control how the clam responds to environmental variables.

Sensitivity analysis results are presented as arc elasticities and figures. Arc elasticities were calculated as the percentage change in tissue dry weight divided by the percentage change in the value of each parameter respectively. The elasticity of TDW with respect to changes in a particular parameter (j) was calculated as:

$$elasticity = \frac{TDW(0.99j) - TDW(1.01j)}{TDW(basej)} \bigg/ \frac{0.99j - 1.01j}{basej} \quad (7.1)$$

Elasticities were calculated at both the median and final $TDWs$ after 5-years growth. Parameters were then ranked according to the magnitude of their influence on TDW . Only the elasticities at the final $TDWs$ are presented here. The elasticities at the median $TDWs$ were very similar in both magnitude and ranking.

7.3.1 Base Case

A base case was defined for *T. crocea* and *T. derasa* using the parameters in Table 7.1. The initial tissue dry weights (TDW_0) for the species were calculated from their initial wet weights (w_0) reported in Table 6.13, using the allometric relationships described in Chapter 5 and the parameter values presented in Table 7.1. The values for TDW_0 were 0.054 g for *T. crocea* and 0.040 g for *T. derasa*. The base-case results are presented in Figure 7.3 for the respective species. The final TDW after 5 years is 13.219 g for *T. crocea* and 11.731 g for *T. derasa*. The corresponding shell lengths (SL , cm) are 10.98 cm for *T. crocea* and 20.10 cm for *T. derasa*.

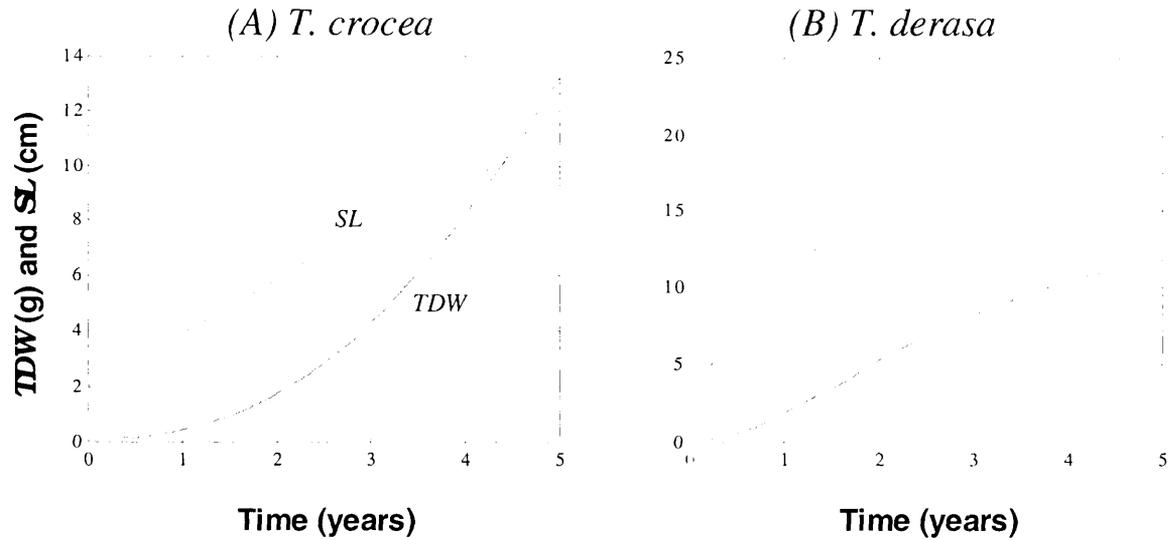


Figure 7.3. Predicted tissue dry weight (*TDW*) and shell length (*SL*) for the base case for both species

7.3.2 Biological Parameters

Elasticities with respect to the biological parameters are presented in Tables 7.2 and 7.3 for *T. crocea* and *T. derasa* respectively. The rankings of the elasticities are very similar for both species. The influence of changing the biological parameters on *TDW* is also illustrated in Figures 7.4 and 7.5 for the respective species.

Critical parameters for both species are the surplus-energy-intake parameters, α_E and β_E . As these parameters increase (decrease), the value of *TDW* decreases (increases) as more (less) energy is expended on unaccounted metabolic processes. By contrast, the effect of changing the surplus-energy-age parameters, α_A and β_A , is minimal for both species. This is due to the short duration over which growth was simulated.

Other parameters to which the model is particularly sensitive include the photosynthesis parameters, TR , α_p and β_p , and the respiration parameters, α_R and β_R . By contrast, the model is not very sensitive to the filter-feeding parameters, AE , α_F and β_F , suggesting that less effort should be made to estimate these parameters as accurately as possible (see Cacho, 1997).

Notably, the elasticities for changes in the husbandry parameter, α_H , and the density parameters, α_M and β_M , are very low. The sensitivity of the model to changes in husbandry and thinning frequency is further investigated in Sections 7.4 and 7.5.

Table 7.2. Sensitivity of predicted tissue dry weight (TDW) of *T. crocea* after 5-years growth to changes in biological parameters

Parameter	Base values	Elasticity at final TDW	Ranking
α_H	0.0185	0.00	16
k_a	0.05	0.33	12
TR	0.95	8.84	5
α_M	16.7507	0.00	17
β_M	0.6392	0.00	18
α_P	2.2186	8.99	4
β_P	0.677	2.64	7
α_R	10.9536	-9.26	3
β_R	0.597	-2.76	6
AE	0.5540	0.82	9
α_F	14.0400	0.82	10
β_F	0.905	0.72	11
α_E	0.4915	-20.03	2
β_E	1.0727	-32.00	1
α_A	0.0003	-0.08	14
β_A	1.5	-0.26	13
α_C	0.8547	2.00	8
β_C	-0.0100	-0.01	15

Table 7.3. Sensitivity of predicted tissue dry weight (TDW) of *T. derasa* after 5-years growth to changes in biological parameters

Parameter	Base values	Elasticity at final TDW	Ranking
α_H	0.0144	0.00	14
k_a	0.05	0.23	12
TR	0.95	6.28	7
α_M	17.5318	0.00	15
β_M	0.7777	0.00	16
α_P	2.1373	6.45	6
β_P	0.744	9.82	3
α_R	18.5029	-7.67	4
β_R	0.736	-11.87	2
AE	0.5463	0.43	10
α_F	14.2457	0.43	11
β_F	0.700	0.61	8
α_E	0.2018	-6.93	5
β_E	1.1788	-39.66	1
α_A	0	0.00	17
β_A	1.5	0.00	18
α_C	0.7899	0.45	9
β_C	0.0058	0.00	13

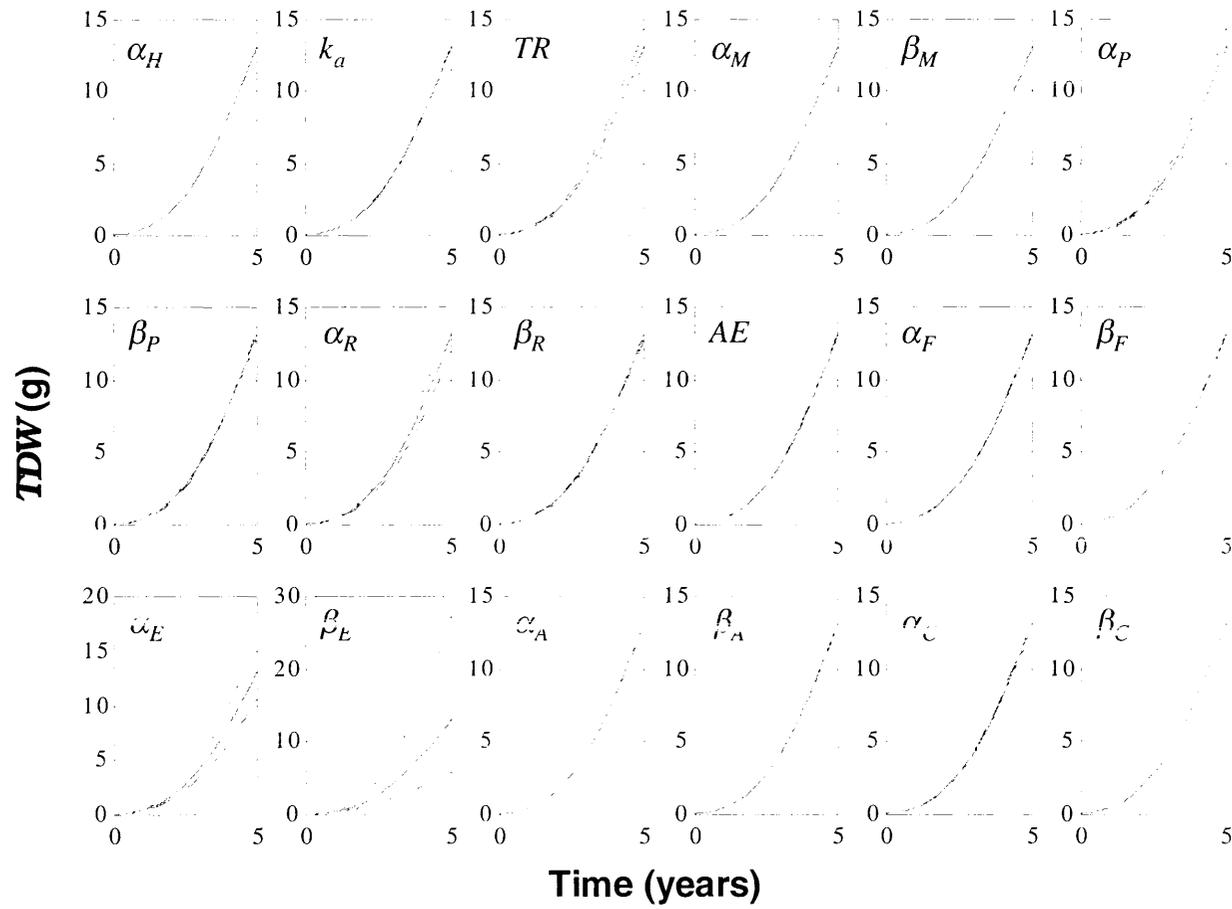


Figure 7.4. Sensitivity of predicted tissue dry weight (TDW)^a of *T. crocea* after 5-years growth to changes in biological parameters^b

^a TDW scale differs for some sub-figures

^b Parameter values: —, base case; ---, 1 percent lower; ···, 1 percent higher

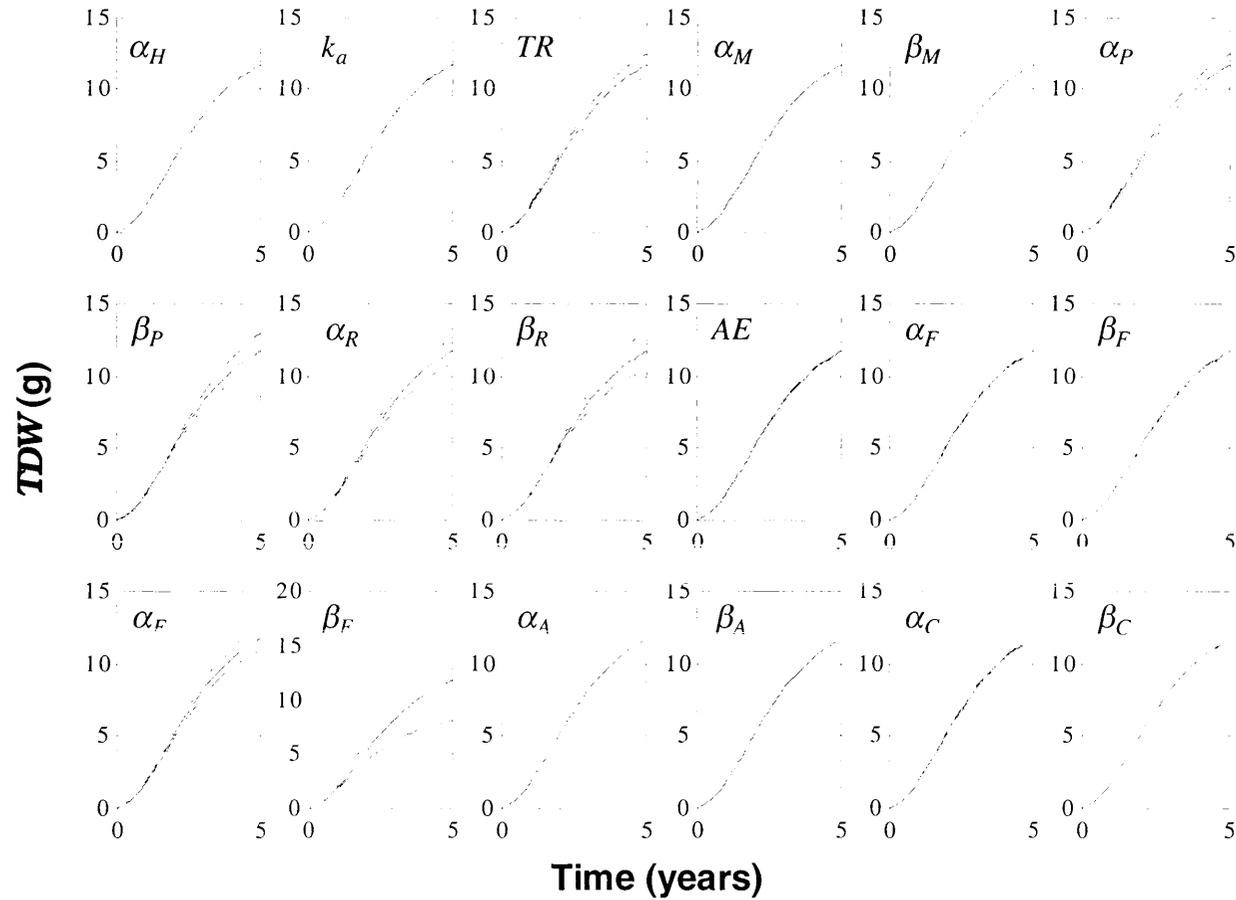


Figure 7.5. Sensitivity of predicted tissue dry weight (TDW)^a of *T. derasa* after 5-years growth to changes in biological parameters^b

^a TDW scale differs for some sub-figures

^b Parameter values: —, base case; ---, 1 percent lower; ···, 1 percent higher

7.3.3 Environmental Parameters

Elasticities with respect to the environmental parameters are presented in Tables 7.4 and 7.5 for *T. crocea* and *T. derasa* respectively. The rankings of the elasticities are the same for both species. The influence of changing the environmental parameters on *TDW* is also illustrated in Figures 7.6 and 7.7 for the respective species.

Critical parameters for both species are the temperature-dependent respiratory-response parameters, ϕ_1 , ϕ_2 , ϕ_3 and ϕ_4 . Elasticities are negative with respect to ϕ_1 and ϕ_2 , and positive with respect to ϕ_3 and ϕ_4 . This is not surprising given the shape of the temperature-dependent respiratory-response function, Ω (see equation (5.25)), which increases with increasing temperature, up to a maximum, and then rapidly decreases as the lethal temperature is approached. The elasticities with respect to $Temp_{max}$ and $Temp_{opt}$ are positive and negative respectively, for the same reason, since the temperature-dependent photosynthetic-response function, Ψ (see equation (5.21)), is of a similar shape to Ω .

Table 7.4. Sensitivity of predicted tissue dry weight (*TDW*) of *T. crocea* after 5-years growth to changes in environmental parameters

Parameter	Base values	Elasticity at final <i>TDW</i>	Ranking
I_k	0.5040	-1.21	6
$Temp_{max}$	38.2172	0.17	8
$Temp_{opt}$	28.5924	-1.81	5
Q_{10}	1.67	-0.27	7
ϕ_1	$30.591e^{-6}$	-9.26	3
ϕ_2	-301.74	-93.93	2
ϕ_3	$71.459e^{-5}$	9.06	4
ϕ_4	-312.26	95.03	1

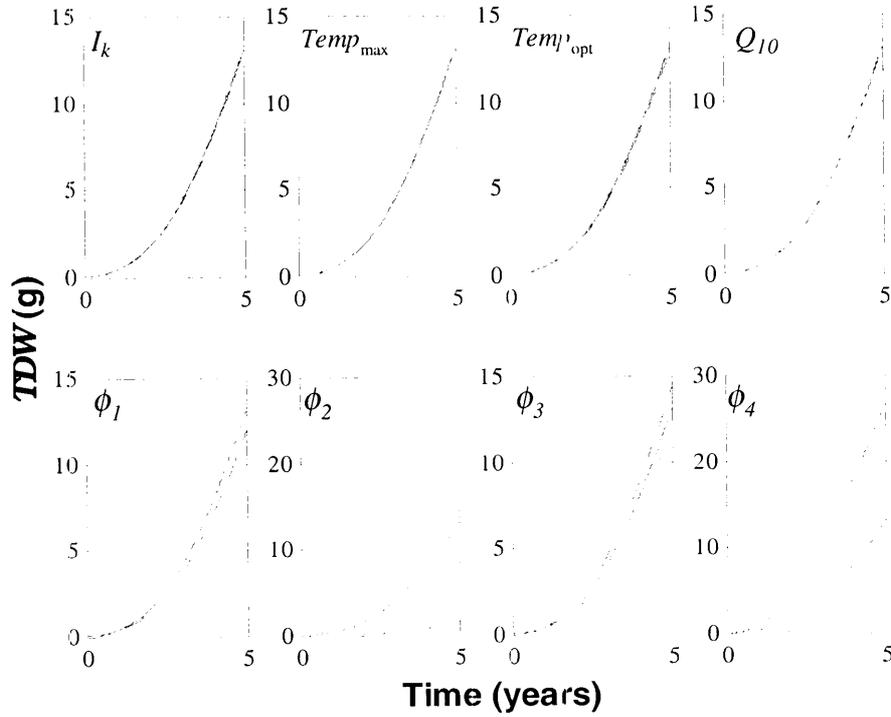


Figure 7.6. Sensitivity of predicted tissue dry weight (TDW)^a of *T. crocea* after 5-years growth to changes in environmental parameters^b

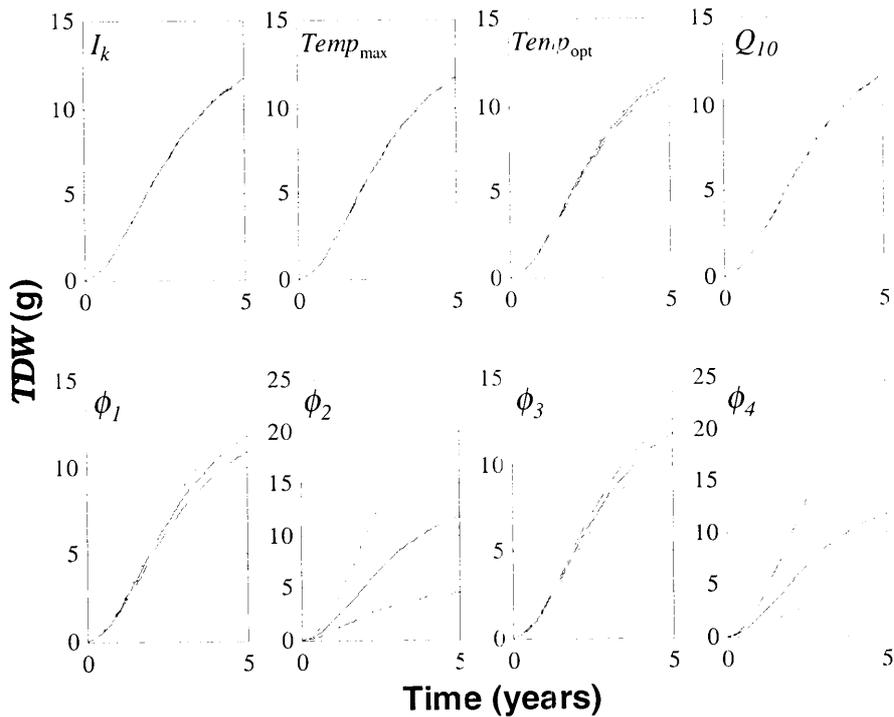


Figure 7.7. Sensitivity of predicted tissue dry weight (TDW)^a of *T. derasa* after 5-years growth to changes in environmental parameters^b

^a TDW scale differs for some sub-figures

^b Parameter values: —, base case; ---, 1 percent lower; - - -, 1 percent higher

Table 7.5. Sensitivity of predicted tissue dry weight (*TDW*) of *T. derasa* after 5-years growth to changes in environmental parameters

Parameter	Base values	Elasticity at final <i>TDW</i>	Ranking
I_k	0.2050	-0.49	6
$Temp_{max}$	38.6966	0.17	8
$Temp_{opt}$	29.0617	-2.49	5
Q_{10}	1.67	-0.29	7
ϕ_1	$30.591e^{-6}$	-7.67	3
ϕ_2	-301.74	-84.69	2
ϕ_3	$71.459e^{-5}$	7.51	4
ϕ_4	-312.26	85.81	1

7.4 Decision Variables

The effect of decision variables on growth was investigated for each species. In the model there are four decision variables: clam-seed size (w_0 , wet weight of tissue plus shell, kg), number of clam seeds planted in the initial cage (N_0), husbandry level (H), and thinning frequency (TF , weeks). The decision vector \mathbf{u} (given by equation (5.8)) is reproduced below:

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

w_0 (or rather its tissue dry weight equivalent, TDW_0) and N_0 were held constant at their base-case values (see Section 7.3 above and Table 6.13), while H and TF were allowed to vary. A 5×7 factorial design was used with five levels of husbandry ($H=1, \dots, 5$) and seven levels of thinning frequency ($TF=26, 52, 78, 104, 156, 208, 260$). The parameter values for each species were taken from Table 7.1 and mortality was assumed to be zero. The model was run for 5 years.

Solving the model for these combinations of the decision variables gives a look-up table for each species for final *TDW* after 5 years (see Tables 7.6 and 7.7 for *T. crocea* and *T.*

derasa respectively). These results are also presented graphically in Figures 7.8 and 7.9 for the respective species.

It is evident that for both species final *TDW* increases with increasing husbandry, and is highest when thinning is most frequent (when $TF=26$). Thinning frequency does not significantly effect the final *TDW* of either species unless it is very infrequent (more than 104 to 156 weeks for *T. crocea* and 78 to 104 weeks for *T. derasa*). When thinning is very infrequent, the clams are crowded and their growth is reduced. Husbandry and thinning are substitute inputs in production, so the village farmer would be able to produce a clam of a given *TDW* by substituting labour between husbandry and thinning activities.

Table 7.6. Predicted tissue dry weight (*TDW*, g) of *T. crocea* after 5-years growth

<i>TF</i> (weeks)	<i>H</i> (scale)				
	1	2	3	4	5
26	4.640	6.567	8.663	10.892	13.219
52	4.640	6.567	8.663	10.892	13.219
78	4.640	6.567	8.663	10.892	13.219
104	4.640	6.567	8.663	10.657	12.112
156	4.640	6.324	7.044	7.426	7.783
208	4.147	4.846	5.275	5.777	6.157
260	2.535	2.653	2.755	2.858	2.968

Table 7.7. Predicted tissue dry weight (*TDW*, g) of *T. derasa* after 5-years growth

<i>TF</i> (weeks)	<i>H</i> (scale)				
	1	2	3	4	5
26	7.644	8.580	9.574	10.625	11.731
52	7.644	8.580	9.561	10.522	11.579
78	7.178	7.877	8.582	9.354	10.118
104	6.081	6.459	6.970	7.388	7.965
156	4.325	4.404	4.483	4.562	4.640
208	4.096	4.248	4.389	4.465	4.560
260	2.033	2.085	2.114	2.148	2.198

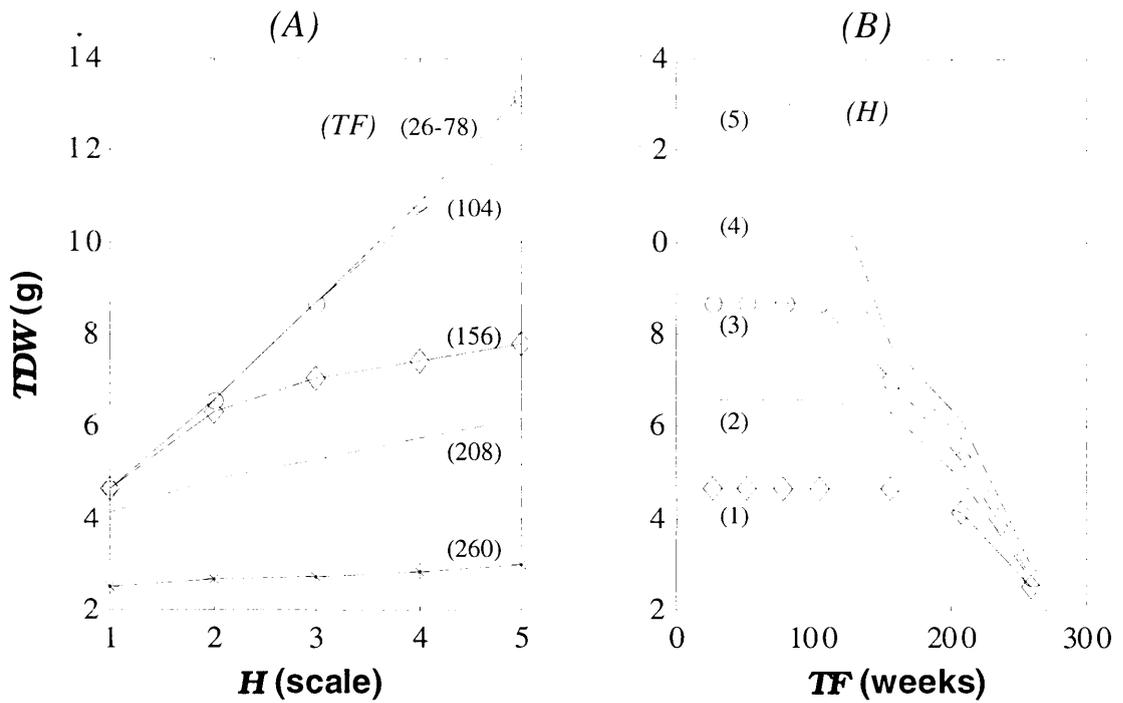


Figure 7.8. Predicted tissue dry weight (*TDW*) of *T. crocea* after 5-years growth

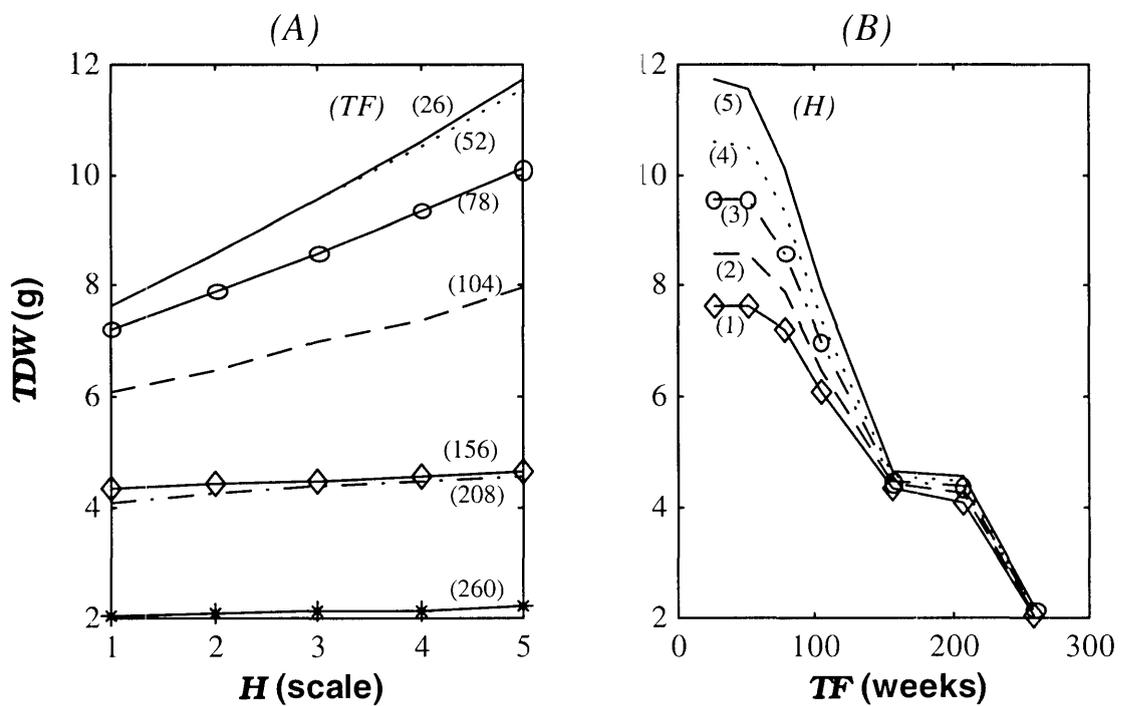


Figure 7.9. Predicted tissue dry weight (*TDW*) of *T. derasa* after 5-years growth

7.5 Isoquant Analysis

The input substitutability between labour and time (ie. cycle-length) in the production of clams of a target size was investigated for both species. The decision variables, husbandry (H) and thinning frequency (TF , weeks), and the cycle-length (T , years) determine the amount of labour (L , hrs) used in production. The effect of H and TF on the combinations of labour and cycle-length that produce *T. crocea* of 1.032 g TDW (ie. 5-cm shell length) and *T. derasa* of 5.088 g TDW (ie. 15-cm shell length) was investigated.

Initially, husbandry was allowed to vary while holding thinning frequency constant. Five levels of husbandry were used ($H=1, \dots, 5$), while thinning frequency was held constant at 26 weeks. Thinning frequency was then allowed to vary while holding husbandry constant. Seven levels of thinning frequency were used ($TF=26, 52, 78, 104, 156, 208, 260$), while husbandry was held constant at 5 (excellent). Running the model for each case provided insight into the substitutability between labour and cycle-length, and between the decision variables and cycle-length. TDW_0 and N_0 were held constant at their base-case values (as was also the case in Section 7.4 above). The parameter values for each species were taken from Table 7.1 and mortality was assumed to be zero.

Model predictions are illustrated in Figures 7.10 and 7.11 for *T. crocea* and *T. derasa* respectively. Charts (A) and (B) of each figure illustrate the input substitutability of labour and cycle-length in response to changes in H and TF respectively. Charts (C) and (D) of each figure illustrate how cycle-length changes in response to changes in H and TF respectively.

It is clear that for both species cycle-length decreases with better husbandry. Better husbandry improves energy intake (see equations (5.14) and (5.15)) and the clams grow to their target size more quickly. Better husbandry generally increases labour input because more time is spent cleaning the clams, even though the cycle-length is shortened. The exception is *T. derasa*, for which improving husbandry from four to five, decreases labour input, and less of both inputs (labour and time) are required for the clams to grow to their target size (see Figure 7.11 (A)).

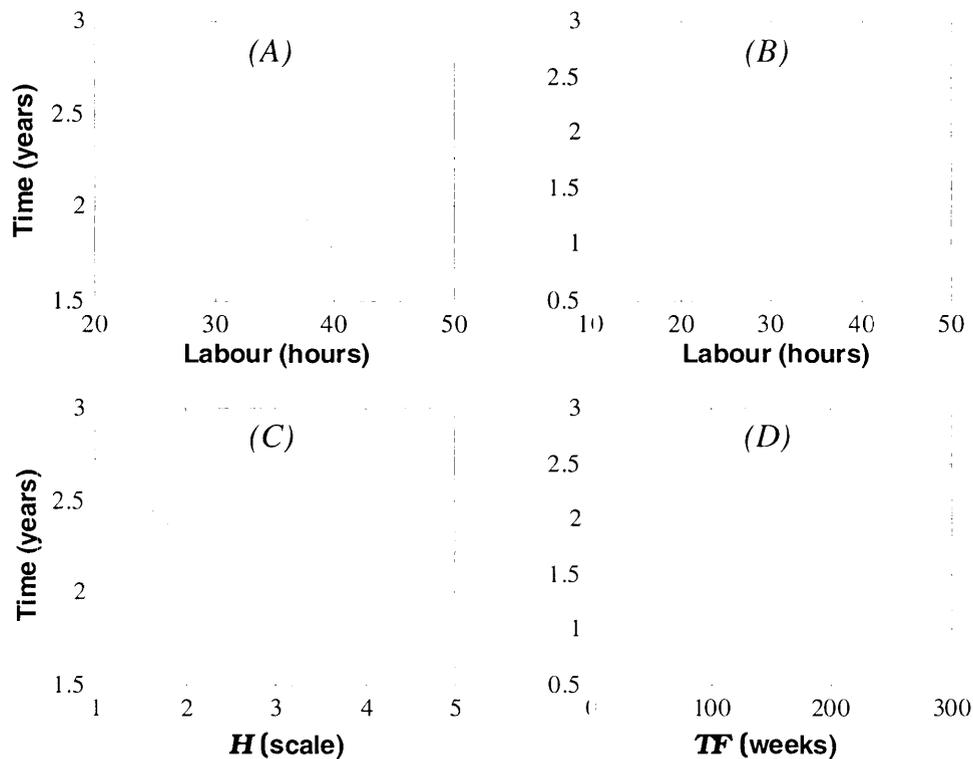


Figure 7.10. Substitutability between labour and time, and between the decision variables and time, for *T. crocea*

Thinning frequency has a very different effect on the respective species. The cycle-length of *T. crocea* is unaffected by increasing the time interval between thinnings (see Figure 7.10 (D)). The clams do not become crowded, so they take the same time to grow to their target size independently of thinning frequency. Labour decreases as thinning becomes more infrequent because cycle-length is unchanged (Figure 7.10 (B)). In contrast, the cycle-length of *T. derasa* increases as the time interval between thinnings increases (see Figure 7.11 (D)). The clams become crowded and their growth slows, so they take longer to reach their target size. Labour initially decreases with less frequent thinning, but then increases (Figure 7.11 (B)). As thinning becomes less frequent over an extended cycle-length, both labour and cycle-length increase. It would be irrational for a village farmer to thin so infrequently that more of both inputs (labour and time) are required for the clams to reach their target size. Dillon and Anderson (1990, p. 35) describe irrational input use in terms of isoquant analysis.

The sensitivity of the model to changes in husbandry and thinning frequency has significant implications for optimal solutions to the economic model in later chapters.

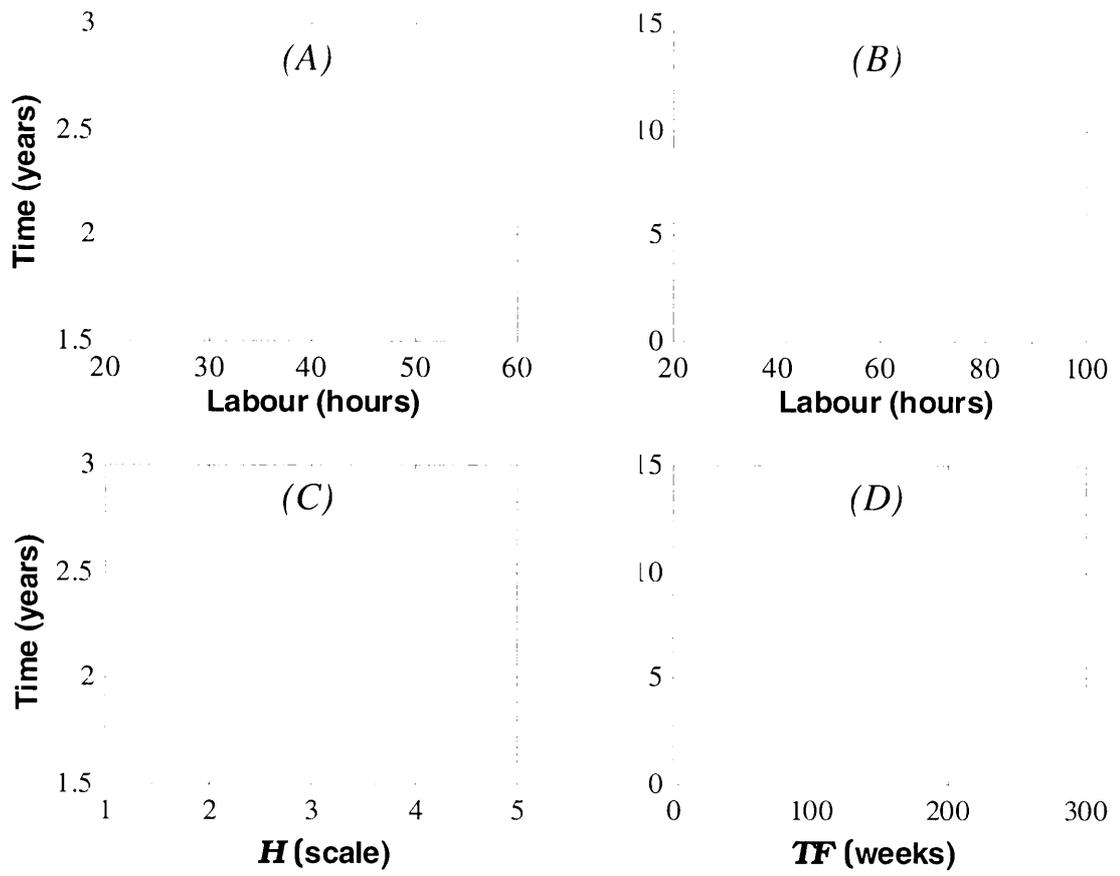


Figure 7.11. Substitutability between labour and time, and between the decision variables and time, for *T. derasa*

8. Optimal management

The bioeconomic model developed in Chapter 5 is applied in this chapter to explore optimal management of the giant-clam operation. This involves finding the combination of the decision variables and the cycle-length that maximises a stream of discounted net benefits. In this chapter, the decision variables considered are husbandry and thinning frequency. The optimal cycle-length is determined for both a single clam harvest and multiple harvests for various management scenarios. The labour requirements for these management scenarios are identified for the multiple-harvest case and the substitutability of labour and cycle-length is investigated. Global optimisation and the sensitivity of optimal management to changes in parameter values are briefly discussed. The model is then used in a hypothetical adoption study to estimate the potential supply of giant clams from Solomon Islands.

8.1 Model Implementation

The model was implemented for both *T. crocea* and *T. derasa*. Base-case parameter values and other assumptions were presented in Tables 6.13 and 7.1. Price functions for clam seed and marketable clams were presented in Figures 6.1 and 6.2 respectively. A discount rate (r) of 6 percent was assumed throughout.

The optimal cycle-length for a single harvest was estimated by maximising equation (5.7) with respect to T (harvest time, years). Equation (5.7) is reproduced below:

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

The optimal cycle-length for multiple harvests was estimated over an infinite time horizon by maximising the function:

$$\pi_T = V_T\{h_T, \mathbf{u}, \mathbf{p}\} \frac{1}{e^{rT} - 1} \quad (8.1)$$

As previously defined, h_T is total clam harvest (kg) at time T , and \mathbf{u} and \mathbf{p} are vectors of decision variables and prices respectively, given by equations (5.8) and (5.9):

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

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

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), while 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.

8.2 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 8.1 (A) and 8.2 (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 (5.7). 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 (5.2)). However, for any given pair of values for H and TF , the optimal cycle-length can be established

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 8.1 (A) and 8.2 (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.

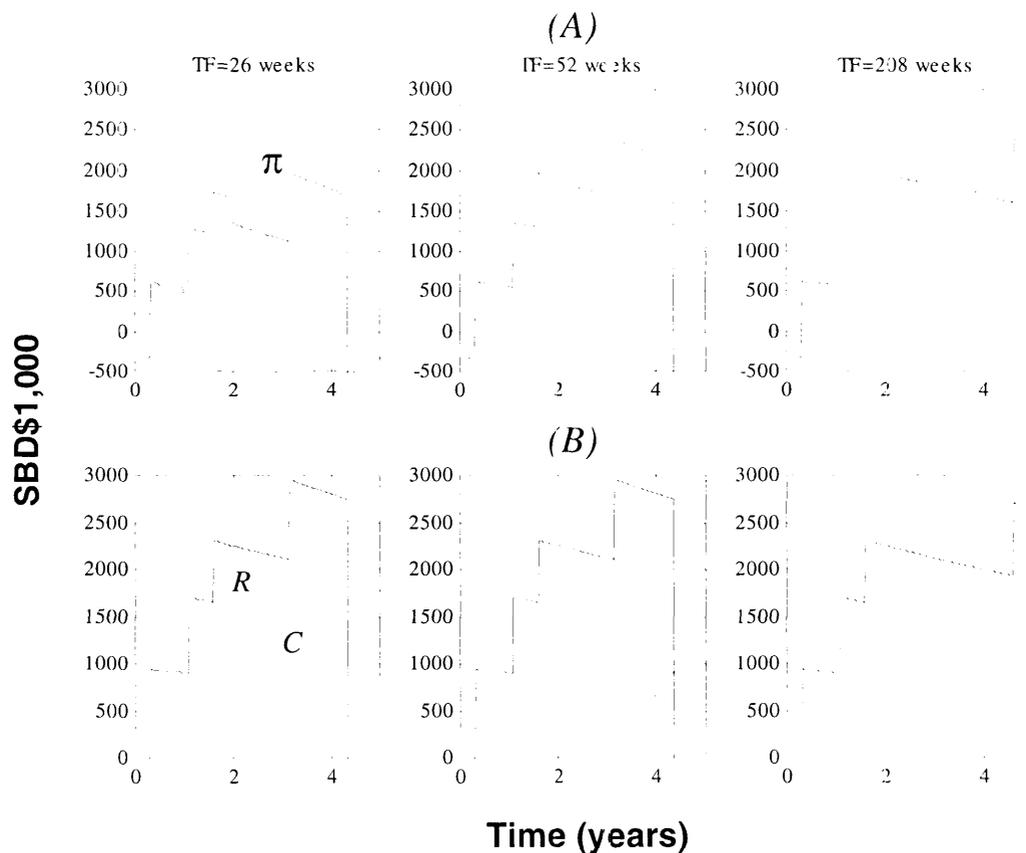


Figure 8.1. (A) Present value of profits (π) and (B) present value of revenues (R) and costs (C) for *T. crocea* for the single-cycle case with zero mortality

The jagged shape of the profit function for *T. crocea* (Figure 8.1 (A)) is due to the step-wise nature of discounted revenues and costs (Figure 8.1 (B)), which in turn are determined by the step-wise price function for marketable clams of this species as presented in Chapter 6 (see Figure 6.2), and the impact of thinning as already

discussed. The shape of the function for *T. derasa* (Figure 8.2) is not as jagged once the clams reach marketable size, because of the linear price function assumed for the marketable clams of this species.

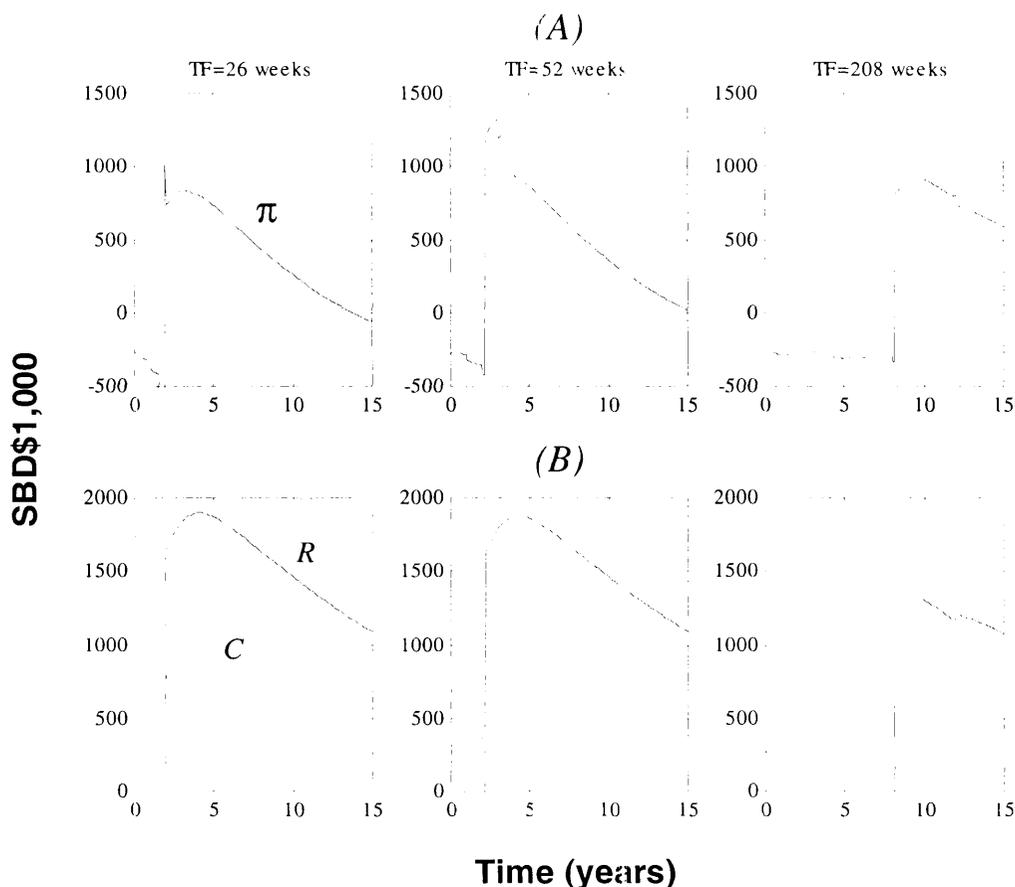


Figure 8.2. (A) Present value of profits (π) and (B) present value of revenues (R) and costs (C) for *T. derasa* for the single-cycle case with zero mortality

The spike in profits for *T. derasa* (Figure 8.2(A)) warrants further explanation. It occurs when the clams reach marketable size one week prior to the next thinning. There is a significant increase in revenues (Figure 8.2(B)), and a corresponding increase in profits (Figure 8.2(A)), when the clams reach 15 cm in shell length. This happens 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 8.2(B)) and a corresponding reduction in profits (Figure 8.2(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 8.1.

Table 8.1. 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	5.95	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. crocea*, T^* is unaffected by thinning frequency when husbandry is very poor ($H=1$) (Table 8.1). 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).

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 8.1). 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.

Table 8.2. Optimal cycle-length (T^* , years) for the single-cycle case for both species, with positive mortality

T. crocea

TF (weeks)	H (scale)				
	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 (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	4.33	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

The model was also solved for the mortality rates presented in Table 6.13; the results are presented in Table 8.2. 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.

8.3 Multiple-cycle optimisation

Equation (8.1) 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 8.3 and 8.4 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.

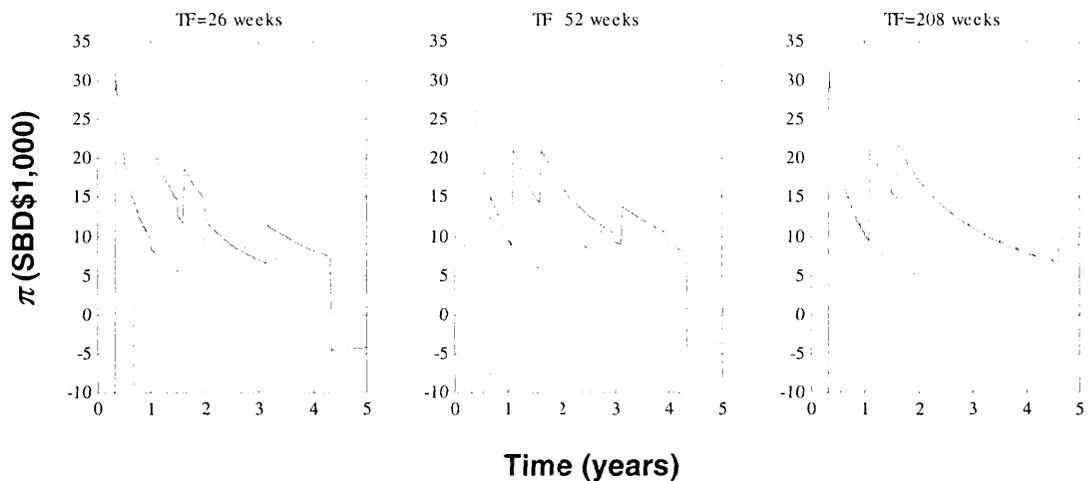


Figure 8.3. Present value of profits (π) for the base case (solid line) and for poor husbandry (dotted line) for *T. crocea* for multiple cycles

For *T. crocea* (Figure 8.3), 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 8.3, where the present value of profits is SBD\$32,068 and SBD\$14,608 for good and poor husbandry respectively. For *T. derasa* (Figure 8.4), 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 8.4).

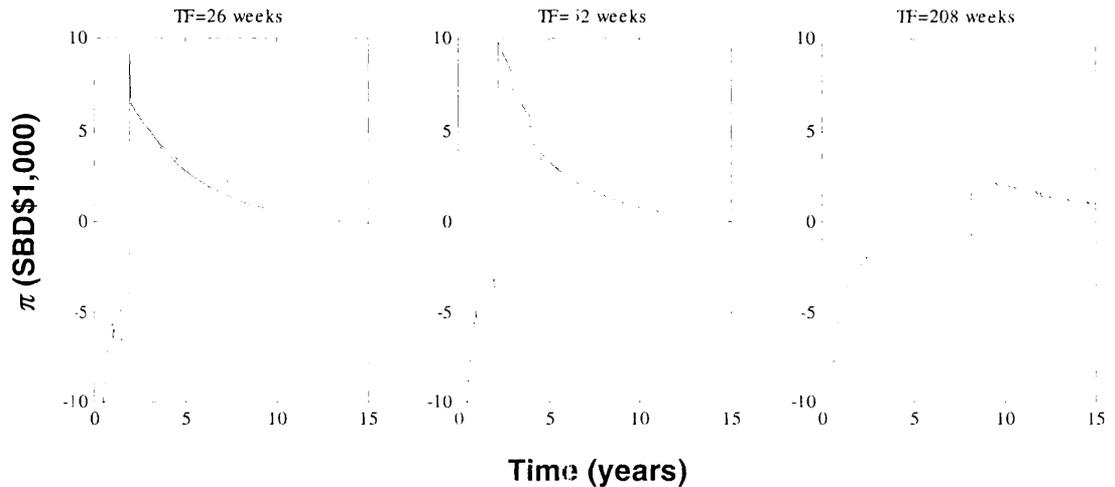


Figure 8.4. Present value of profits (π) for the base case (solid line) and for poor husbandry (dotted line) for *T. derasa* for multiple cycles

Look-up tables for the selected combinations of the decision variables H and TF for the multiple-cycle case are presented for *T. crocea* and *T. derasa* in Table 8.3 for zero mortality, and Table 8.4 for positive mortality. The model outputs in the look-up tables are 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 the zero-mortality case for *T. crocea* (Table 8.3), T^* decreases with increasing husbandry, but is unaffected by thinning frequency. The opportunity cost of harvesting early is low, so T^* is very short, and the clams are harvested soon after they reach their marketable size of 2.54-cm shell length; hence h^* is fairly constant. Thinning is only undertaken when $H=1, 2$ and $TF=26$; for all other combinations of the decision variables, T^* is so short that labour is used for husbandry alone. L^* and π^* therefore increase with increasing husbandry, and are only affected by thinning frequency when $H=1, 2$ and $TF=26$. π^* is highest when husbandry is excellent ($H=5$). T^* is so short (0.33 years), that there is insufficient time for thinning to be undertaken.

In the zero-mortality case for *T. derasa* (Table 8.3), T^* increases as TF increases. This is because the clams become crowded when thinning is infrequent and take longer to grow to their marketable size of 15-cm shell length. T^* generally decreases

as H increases, but this trend is confused when combinations of H and TF result in crowding. For example, when $H=3, \dots, 5$ and $TF=260$, crowding pushes T^* to 11 years and it is optimal to harvest the clams when they are 16-18 cm in shell length (ie. the returns from harvesting a larger clam outweigh the opportunity cost of delaying harvest). For all other combinations of the decision variables it is optimal to harvest the clams earlier, mostly when they are around 15-cm shell length. T^* is sufficiently long that thinning is undertaken for all combinations of H and TF . L^* increases as H increases and decreases as TF increases. π^* tends to increase with increases in H and decreases in TF , because T^* is reduced. h^* is maximised when $H=5$ and $TF=260$, but π^* is very low for this level of production because T^* is so long (11.05 years). π^* is highest when $H=5$ and $TF=52$.

Table 8.3. Optimal results for the multiple-cycle case for both species, with zero mortality

<i>T. crocea</i>					
<i>TF</i> (weeks)	<i>H</i> (scale)				
	1	2	3	4	5
	Optimal cycle-length (T^* , years)				
26 to 260	0.67	0.54	0.44	0.38	0.33
	Maximum discounted profits (π^* , SBD\$)				
26	14608	18300	23652	27224	32068
52 to 260	15477	19393	23652	27224	32068
	Optimal labour usage (L^* , hr/cage/year)				
26	19.4	25.6	26.4	31.3	37.4
52 to 260	15.6	20.9	26.4	31.3	37.4
	Harvest (h^* , kg)				
26 to 260	0.58	0.59	0.59	0.60	0.59
	Shell length (SL^* , cm)				
26 to 260	2.54	2.55	2.55	2.57	2.55

Table 8.3. cont.

T. derasa

<i>TF</i> (weeks)	<i>H</i> (scale)				
	1	2	3	4	5
Optimal cycle-length (T^* , years)					
26	2.88	2.61	2.32	2.13	1.98
52	2.88	2.61	2.32	2.21	2.19
78	3.45	3.18	3.20	3.16	3.07
104	4.39	4.20	4.20	4.14	4.14
156	6.21	6.16	6.29	6.35	6.39
208	8.23	8.36	8.40	8.84	8.96
260	10.38	10.89	10.39	11.01	11.05
Maximum discounted profits (π^* , SBD\$)					
26	4638	4971	5506	5988	9261
52	7441	8224	9260	9770	9820
78	6089	6618	6520	6572	6743
104	4642	4844	4795	4839	4858
156	3103	3097	3037	3050	3055
208	2194	2152	2162	2194	2176
260	1624	1635	1683	1641	1653
Optimal labour usage (L^* , hr/cage/year)					
26	7.1	16.5	23.1	27.3	28.5
52	5.4	8.7	11.5	13.8	16.1
78	4.5	7.0	9.2	11.3	13.2
104	3.5	5.8	7.9	10.0	12.0
156	2.5	4.6	6.7	8.9	11.1
208	1.9	4.0	6.1	8.6	11.0
260	1.5	3.7	5.7	8.2	10.5
Harvest (h^* , kg)					
26	76.27	76.59	76.05	76.05	75.99
52	76.27	76.59	76.05	76.72	76.88
78	76.20	76.48	76.35	76.68	76.10
104	75.92	76.24	76.14	76.61	79.38
156	76.30	76.38	80.94	87.78	93.60
208	76.08	80.30	87.00	115.88	125.98
260	76.36	99.95	95.80	120.57	133.53
Shell length (SL^* , cm)					
26	15.02	15.04	15.01	15.01	15.01
52	15.02	15.04	15.01	15.05	15.06
78	15.02	15.03	15.03	15.05	15.01
104	15.00	15.02	15.01	15.04	15.20
156	15.02	15.03	15.28	15.65	15.95
208	15.01	15.25	15.61	16.97	17.39
260	15.03	16.25	16.05	17.16	17.68

Mortality has no effect on the results for *T. crocea* except where $H=1, 2$ and $TF=26$ (compare Tables 8.3 and 8.4). For these combinations of the decision variables T^* is the longest so mortality has its greatest effect. Less labour is required for thinning because there are fewer clams; this also has the effect of reducing capital input since less cages are required on the farm. Even though production costs fall, profits are reduced because h^* , and therefore revenue, are much lower. For *T. derasa*, mortality again ameliorates the effect of crowding evident in the zero-mortality results for this species (compare Tables 8.3 and 8.4). Mortality reduces the extent of crowding, so T^* is shorter when thinning is infrequent, and consistently decreases with increases in husbandry, since the clams can grow more quickly to their marketable size. Less labour is generally used because there are fewer clams to thin (so less capital is generally used as explained above) and the cycle-length is shorter. h^* is also reduced. Nevertheless, for most combinations of the decision variables, π^* is higher because T^* is significantly reduced, and production costs fall far more than revenue. π^* is still highest when $H=5$ and $TF=52$.

Table 8.4. Optimal results for the multiple-cycle case for both species, with positive mortality

<i>T. crocea</i>					
TF (weeks)	<i>H</i> (scale)				
	1	2	3	4	5
	Optimal cycle-length (T^* , years)				
26 to 260	0.67	0.54	0.44	0.38	0.33
	Maximum discounted profits (π^* , SBD\$)				
26	7863	9834	23652	27224	32068
52 to 260	15477	19393	23652	27224	32068
	Optimal labour usage (L^* , hr/cage/year)				
26	16.1	21.5	26.4	31.3	37.4
52 to 260	15.6	20.9	26.4	31.3	37.4
	Harvest (h^* , kg)				
26	0.41	0.41	0.59	0.60	0.59
52 to 260	0.58	0.59	0.59	0.60	0.59
	Shell length (SL^* , cm)				
26 to 260	2.54	2.55	2.55	2.57	2.55

Table 8.4. cont.

T. derasa

<i>TF</i> (weeks)	<i>H</i> (scale)				
	1	2	3	4	5
Optimal cycle-length (T^* , years)					
26	2.88	2.61	2.32	2.13	1.98
52	2.88	2.61	2.32	2.13	1.99
78	3.15	3.05	2.97	2.84	2.68
104	3.85	3.68	3.34	3.13	2.95
156	4.49	4.22	4.03	3.93	3.82
208	5.33	5.04	4.95	4.83	4.74
260	6.18	6.04	5.98	5.87	5.81
Maximum discounted profits (π^* , SBDS)					
26	4089	4367	4323	5236	8445
52	6719	7421	8352	9129	9755
78	5781	5945	6932	7217	7634
104	5116	5345	5923	6336	6710
156	4101	4362	4569	4663	4791
208	3206	3383	3433	3488	3540
260	2563	2597	2637	2691	2705
Optimal labour usage (L^* , hr/cage/year)					
26	6.8	15.8	22.3	26.6	28.2
52	5.2	8.4	11.2	13.4	15.3
78	4.6	6.8	8.1	10.2	12.2
104	3.2	5.3	7.4	9.3	11.1
156	2.7	4.6	6.3	7.9	9.5
208	2.2	3.9	5.5	7.1	8.5
260	1.9	3.5	5.0	6.5	8.0
Harvest (h^* , kg)					
26	70.40	70.69	70.20	70.20	71.56
52	70.40	70.69	70.20	70.20	70.05
78	67.46	67.77	72.49	71.55	71.58
104	70.09	70.20	70.08	70.23	70.12
156	67.30	67.33	67.54	67.58	67.62
208	65.09	64.96	65.24	64.81	64.80
260	62.51	62.36	65.05	66.46	67.25
Shell length (SL^* , cm)					
26	15.02	15.04	15.01	15.01	15.01
52	15.02	15.04	15.01	15.01	15.00
78	15.01	15.03	15.06	15.01	15.01
104	15.00	15.01	15.00	15.01	15.00
156	15.00	15.00	15.02	15.02	15.02
208	15.03	15.02	15.04	15.01	15.01
260	15.03	15.02	15.20	15.30	15.35

As explained in Chapter 5, the optimal cycle-length should be shorter in the multiple-cycle optimisation, so long as the opportunity cost of delaying the harvest, in equation (5.5), is positive (see Section 5.1). The expected results were obtained for both *T. crocea* and *T. derasa* for both the zero- and positive-mortality cases, 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 (i.e. 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 8.5 for *T. crocea* and *T. derasa* respectively for zero mortality and 26-weekly thinning. At a husbandry of five in Figure 8.5 (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 (also see Tables 8.1 and 8.3).

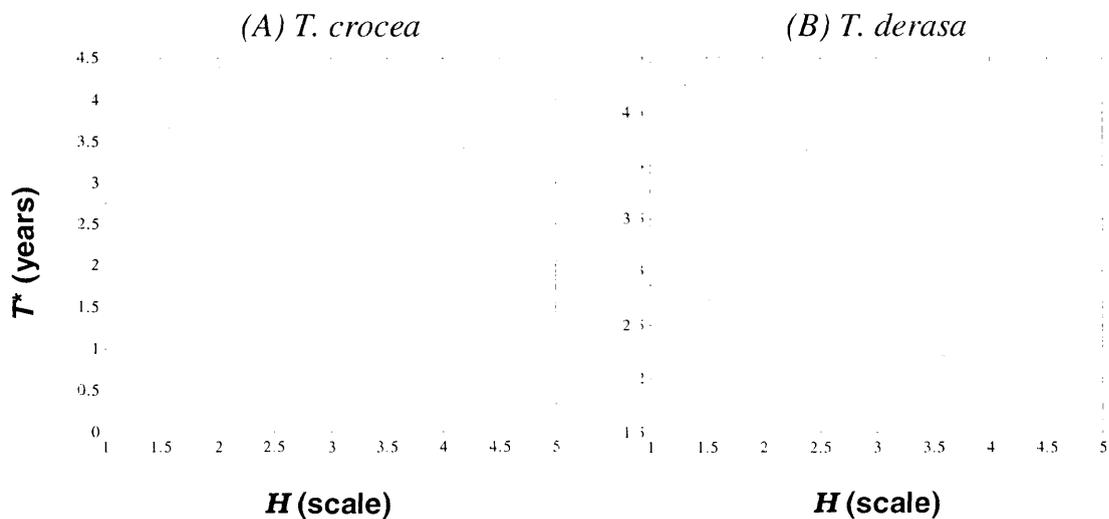


Figure 8.5. Optimal cycle-length (T^*) for the multiple-cycle case (solid line) and for the single-cycle case (dotted line) for both species, for 26-weekly thinning with zero mortality

8.4 Input substitution

In Chapter 7 the input substitutability between labour and cycle-length was investigated in terms of isoquant analysis. Input substitution is considered here between optimal combinations of labour and cycle-length for which the level of production is not the same, hence this analysis differs from that presented in the previous chapter.

Labour usage increases as cycle-length decreases, indicating that labour and time are substitute inputs in production (Figure 8.6). This trend is consistent only for *T. crocea*; it holds for all thinning frequencies in both the zero- and positive-mortality cases. A plot of labour usage for 52-weekly thinning against optimal cycle-length for the zero-mortality case clearly illustrates the trade-off between L^* and T^* for *T. crocea* (see Figure 8.6 (A)). The slope of this curve means that, under optimal management, time from seeding to harvest can be decreased by 0.016 years (5.7 days) for each additional hour of labour used per cage seeded per year. This tradeoff also applies for $TF=78, \dots, 260$, since L^* and T^* are the same for these thinning frequencies.

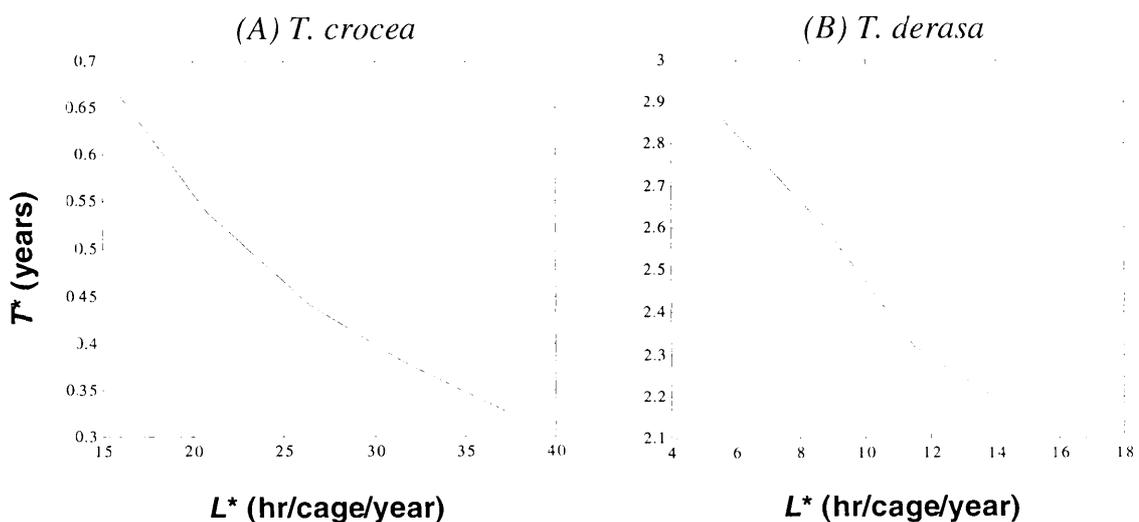


Figure 8.6. Substitutability between optimal labour usage (L^*) and optimal cycle-length (T^*) for both species, for 52-weekly thinning with zero mortality

For *T. derasa*, this relationship holds consistently only for the positive-mortality case; it does not hold for all thinning frequencies in the zero-mortality case. When thinning is infrequent, both L^* and T^* increase as husbandry increases for many combinations of the decision variables, because the clams become crowded (see Table 8.3 and the discussion in the previous section). However, at a thinning frequency of 52 weeks, labour and time are also substitute inputs in the production of this species (see Figure 8.6 (B)). In this case, optimal cycle-length can be decreased by 0.064 years (23.5 days) for each additional hour of labour used per cage seeded per year.

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).

8.5 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). Cacho (1998) discusses 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 study.

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 study given the uncertainty about how the markets for giant-clam products will develop.

8.6 Hypothetical adoption study

In this section, the bioeconomic model is used in a hypothetical adoption study to estimate the potential supply of giant clams from Solomon Islands. The Solomon Island has 5310 km of coastline (www.odci.gov/ia/publications/factbook/). Although fringing reef for giant-clam farming may not be the limiting factor (Bell, 1997, pers. comm.), it is assumed that only 50 percent of the coastline is suitable for giant-clam farming and that a maximum of one farm can be situated every 5 km. Potential adoption for this scenario is therefore 531 farms. ICLARM considers that the maximum manageable farm size is 70 cages (Gervis *et al.*, 1995), so potential adoption is 37,170 cages.

Under optimal management, T^* and π^* for *T. crocea* are 0.33 years and SBD\$32,068 respectively, and 160 clams are harvested from one cage for each cycle. For *T. derasa*, T^* , π^* and h^* are 1.99 years, SBD\$9,755 and 70.05 kg, and 92 clams are harvested from each of two cages for each cycle. For this study it was assumed that it is only practical to harvest two crops of *T. crocea* per year and one crop of *T. derasa* every 2.5 years. Based on this information, the number of clams harvested per cage per year is 320 and profit per cage per year is SBD\$1,257 for *T. crocea*. For *T.*

derasa, 37 clams are harvested per cage per year, 14 kg of clams are harvested per cage per year, and profit is SBD\$220 per cage per year.

Adoption is assumed to follow a logistic pattern: it is very low in the first year (0.01 percent) and increases to 50 percent by year 30. Based on these assumptions 18,585 cages are farmed in year 30.

If all the cages are used for farming *T. crocea* for the aquarium market, nearly 6 million clams are harvested in year 30 (Figure 8.7) at a profit of over SBD\$23M. In 1995, estimated sales of giant clams to the aquarium market were only between 60,000 and 100,000 clams (Gervis *et al.*, 1995). Potential supply estimated in this study is therefore unrealistic given the aquarium market is a limited niche market, likely to be supplied by a range of developing countries. Actual supply from Solomon Islands and elsewhere may be curtailed by contracts limiting the number of aquarium farmers or the level of their production.

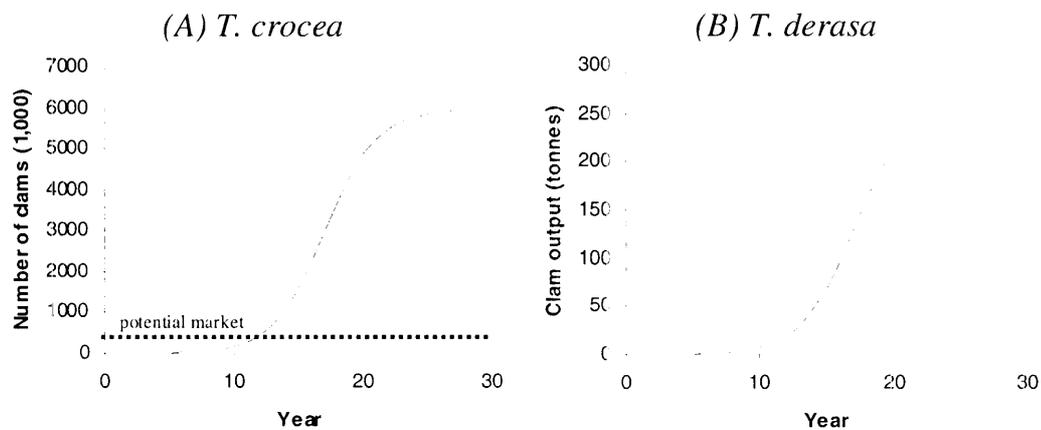


Figure 8.7. Potential industry supply pattern for both species

If all the cages are used for farming *T. derasa* for the seafood market, nearly 690,000 clams are harvested in year 30 at a profit of more than SBD\$4M. Total clam harvest is 260 tonnes (Figure 8.7), this represents about 3.5 tonnes of clam meat (based on the allometric relationships described in Chapter 5 and the parameter values in Table 7.1). Although farming clams for the aquarium market is more profitable, large-scale adoption will depend on development of the seafood market, and this supply-growth scenario is more plausible

These results are based on base prices for marketable clams which were presented in Chapter 6. They are held constant for the duration of the study. There is a lot of uncertainty about how the markets for giant-clam products will develop. If market demand develops faster than adoption, then prices can be expected to increase, whereas if too many farmers enter the industry prices can be expected to fall. Price movements over time, perhaps accompanied by a limit on adoption of giant-clam farming for the aquarium market based on contracts, will shape growth of the emerging industry in Solomon Islands and elsewhere.

This hypothetical adoption study could have been expanded into an industry-level evaluation of the farming system by including potential harvest figures in an equilibrium displacement model to show how this increasing supply would affect the overall market. Such analysis is out of the scope of this study.

Whatever adoption pattern eventuates, transport costs may significantly affect the viability of farms in distant areas. This effect is not picked up in the model given the assumption that marketing services are a factor of harvest size rather than the distance the harvest needs to be transported from the farm to the exporter (see Section 6.2.4).

8.7 Summary

This study has investigated the optimal cycle-length in farming *T. crocea* and *T. derasa*. The results of simulation modelling suggest that for *T. crocea*, maximum profits are obtained with excellent husbandry and no thinning. This is when optimal cycle-length is at its shortest and labour usage is most intensive. This outcome is partly due to the low price of labour and occurs under unconstrained profit maximisation; it is unaffected by mortality. Due to crowding for many combinations of the decision variables, maximum profits for *T. derasa* are achieved when husbandry is excellent and thinning is quite frequent. Optimal cycle-length is relatively short compared to other combinations of the decision variables for this species, and labour usage is relatively high. This result is similarly unaffected by mortality.

This analysis also shows that, although the traditional forestry model presented in Chapter 5 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 respective species.