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by

Robyn L. Hean and Oscar J. Cacho

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Optimal management of giant-clam farming in Solomon Islands[*]

Robyn L. Hean and Oscar J. Cacho[**]

Abstract

Giant-clam farming is undertaken by coastal villagers in Solomon Islands as part of a research and development project of the International Center for Living Aquatic Resources Management (ICLARM). The production technology is simple and does not require a large capital investment. The main inputs are clam seed, labour and time. Labour is used for activities such as seeding, cleaning, thinning and harvesting. In this paper, a bioeconomic model is used to explore optimal farm management. The theoretical basis for this analysis is found in the economic theory of optimal forestry exploitation. The management variables considered are husbandry applied to cleaning and the frequency with which thinning is undertaken. The optimal cycle-length is determined for both a single clam harvest and multiple harvests. The labour requirements of various management scenarios are identified for the multiple-cycle case.

Key Words: bioeconomics; giant clams; subsistence mariculture

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[**] Robyn Hean is a PhD student in the Graduate School of Agricultural and Resource Economics at the University of New England. Oscar Cacho is a Senior Lecturer in the School of Economic Studies, and a member of the Graduate School of Agricultural and Resource Economics at the University of New England. Contact information: Graduate School of Agricultural and Resource Economics, University of New England, Armidale, NSW 2351, Australia. Email: rhean1@metz.une.edu.au.

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Introduction

Giant clams (family *Tridacnidae*) are bivalve molluscs which occur naturally in only the tropical and subtropical marine waters of the Indo-Pacific region. There are nine extant species, of which the largest is *Tridacna gigas* and the smallest is *T. crocea*. Classification keys to the most common species can be found in Rosewater (1965, 1982) and Lucas (1988). Giant clams are characterised by a scaly shell and coloured mantle, and are unique by virtue of a symbiotic relationship with algae that reside within their mantle tissue and convert sunlight through photosynthesis into nutrients for the clam. They are essentially autotrophic, although they may supplement their nutrition by filter-feeding of particulate organic matter from the surrounding seawater (Klumpp *et al.* 1992; Klummp and Griffiths 1994).

Commercial mariculture of giant clams has emerged over recent years in developing countries of the Indo-Pacific region as a result of numerous research and development projects funded by organisations such as the Australian Centre for International Agricultural Research (ACIAR). A variety of mariculture techniques have been developed and are documented comprehensively in culture manuals – eg, Heslinga *et al.* (1990), Braley (1992) and Calumpong (1992). The most widely-used technique to date involves giant clams spending up to their first year in land-based facilities and then being transferred to the ocean for growout (Tisdell and Menz 1992). Four main phases may be distinguished: hatchery phase, land-based nursery phase, ocean-nursery phase and ocean-growout phase. The marketing opportunities for maricultured giant clams have also been investigated and described by many authors including Dawson (1986), Dawson and Philipson (1989), Heslinga *et al.* (1990), Shang *et al.* (1991), Braley (1992), Calumpong (1992), Tisdell (1992), Tisdell *et al.* (1994)

and Riepen (1998). The three main markets identified so far are as aquarium specimens, seafood and shells. The only active market to date is the aquarium market (Gervis *et al.* 1995).

The International Center for Living Aquatic Resources Management (ICLARM) is involved in both research into mariculture techniques and market development, through a project aimed at the commercialisation of village-based giant-clam farming in Solomon Islands. ICLARM conducts this project through its Coastal Aquaculture Centre (CAC) which it established near Honiara in Solomon Islands in 1987. The focus of the project is an extensive program of village-farming trials where selected villagers rear giant clams in ocean nurseries and growout systems for experiments and commercial sale. The trials are designed to identify the optimal environmental conditions and husbandry techniques for village farming and are based on the production of giant clams to test and develop new and existing markets. Results of the trials are the subject of ongoing publications – eg., Govan (1993), Hambrey and Gervis (1993), Bell *et al.* (1997), Foyle *et al.* (1997) and Hart *et al.* (in review).

ICLARM currently distributes seed clams to some 50 village farmers spread across Solomon Islands, who are producing giant clams for aquarium specimens and seafood. The farming systems are simple, low-cost and low-input operations. They typically involve rearing giant clams in sea cages raised above the sea floor on trestles until they are large enough to be virtually free from predation and able to withstand environmental stresses, when they are then placed directly on the sea floor. The main inputs to production are clam seed, labour and time. No feeding is required as the clams obtain their nutrition from photosynthesis and by filter-feeding. Labour input is required for activities such as seeding, cleaning, thinning and harvesting. Seeding consists of putting small clams into cages and fixing cages to trestles on a fringing reef. Cleaning is an important activity; it involves keeping cages free of predators and algal build-up. Thinning involves reducing the number of clams per cage (increasing the number of cages) as they grow; it is undertaken to avoid the negative effects of crowding. Harvesting involves collecting clams of marketable size from the cages and preparing them for transport and sale.

Although village farmers may not be profit-maximisers, it is of economic interest to undertake a normative study of their production system. This involves finding the set of controllable inputs that maximises a stream of discounted net benefits. The controllable inputs are clam-seed density and size, growing-cyclelength, and labour. Given increasing pressure on villagers to progress from a subsistence lifestyle to a cash economy, profit is becoming more important. Although other behavioural assumptions can be investigated with the model described below, profit maximisation is taken as the only objective in this paper. A bioeconomic model of giant-clam farming based on the well developed forestry-rotation literature (eg. Samuelson 1976; Comolli 1981) forms the basis of this study. The model is implemented for the smallest giant-clam species, *T. crocea*, which is the preferred species for the aquarium market. The model is used to determine the optimal cycle-length and to investigate the substitutability of cycle-length and labour.

Theoretical Basis

The theoretical basis for this study is found in the economic theory of optimal forestry exploitation. Its application to giant-clam mariculture has been well established by the studies of Tisdell *et al.* (1993) and Leung *et al.* (1994). Both giant-clam and forestry operations are characterised by a long delay between seeding (or planting) and harvesting. The problem is to determine the optimal time between planting and harvesting (the cycle-length). Assuming that both costs and revenues are incurred at the end of a production cycle, the rules for optimal cycle-length are derived below.

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

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

where $p(T)$ is the present value of the profit, *V(T),* obtained at the end of a cycle of T years, and r is the discount rate. Equation (1) is maximised when:

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

This states that it is optimal to delay harvest until the specific growth rate in the value of the clams equals the discount rate. Equation (2) is sometimes called the Fisher rule (Bjorndal 1988; Hean 1994) for the single-cycle solution. At this point $T = T^*$.

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

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

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

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

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

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

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

Equation (5) can be manipulated to yield the Faustmann rule, where the proportional increase in the future value of profits equals the discounted value of the interest rate:

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

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

The Clam Model

The model used for this study comprises an economic and a biological model. The economic model is outlined below. The biological model is presented in Hean and Cacho (1997) and is not described in detail here.

Economic Model

The economic model describes the costs and revenues associated with clam farming from seeding through to harvest. It is assumed that costs are incurred at the end of the cycle, when revenues are also obtained. This is not unrealistic since ICLARM provides seed clams and the materials for cage and trestle construction to village farmers on credit. In the model, only one cage of clams is seeded at the start of the planning horizon and there is no mortality so that all clams survive through to harvest.

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

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

where h_T is total clam harvest (kg) at time T and $\mathbf{u}$ and $\mathbf{p}$ are vectors of decision variables and prices, respectively. There are four decision variables: seed size (w_0), number of seeds per cage (N), husbandry level (H), and thinning frequency (TF), thus:

$$\mathbf{u} = \left[w_0, N, H, TF\right] \tag{8}$$

The price vector is:

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

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

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

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

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

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

where P_C is measured in US$ and X_r is the exchange rate between SBD$ and US$. The labour ($L$) and capital ($K$) inputs over the period $(0,T)$ and the final harvest (h_T) depend on the decision variables **u**. Labour is used for seeding, cleaning, thinning and harvesting, while capital inputs include cages and trestles. The price of marketing services (P_M) includes the cost of internal freight and transport from the village farm to the exporter, while P_S and P_C are step functions of the initial and final weight of the clams (Figure 1).

The harvest is given by:

$$h_T = N\, w_T\{\mathbf{u}\} \tag{13}$$

where w_T is the average weight (kg) of the clams harvested and is estimated by the biological model as:

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

G_t is clam growth in terms of carbon (mg/day) and r_t is a factor that accounts for carbon partition within the clam and converts carbon weight to clam weight.

The Labour Input

Estimating the use and cost of labour and the relationship between labour and the decision variables is not trivial. Labour is used for different tasks at various times of the year. The amount of labour required over a production cycle depends on the number of clams seeded (N), the husbandry level (H), the frequency of thinning (TF) and the final weight of the clams (w_T) as shown in Table 1.

Husbandry, which refers to the amount of cleaning, is measured on a scale from 1 (very poor) to 5 (excellent). The relationship between L and H was assumed to be linear, and was estimated following discussions with ICLARM staff (Table 1). The effect of husbandry on clam growth is explained in the next section. Thinning is assumed to involve halving the number of clams per cage (doubling the number of cages) and is undertaken until the number of cages on the farm reaches a maximum of 16.

Village farmers do not generally participate in the formal labour market and, thus, the value of their labour is not easy to measure. Solomon Island villagers engage in activities such as gardening and fishing to provide food for the household; any surplus vegetables or fish may be sold in the markets to provide a small amount of cash income. Occasionally, villagers engage in copra production and receive a wage. Based on these observations, and on informal interviews with clam farmers, the opportunity cost of their labour was estimated to be quite low (SBD$1.50/hr) and was taken as the wage rate (P_L).

Biological Model

The biological model describes the growth of the individual giant clam in terms of an energy budget, in which growth is the difference between energy intake and energy expenditure. Energy intake is from photosynthesis and filter-feeding, while energy expenditure is on routine respiration (or maintenance metabolism) and surplus energy expenditure (on metabolic processes such as reproduction). The model is implemented using SIMULINK© and MATLAB© (Mathworks 1992). It is dynamic and nonlinear and comprises a set of differential equations which are solved by numerical integration. Inputs to the model are environmental and management variables, and output is the time trajectory of clam weight (w_t). An early version of the model is described by Hean and Cacho (1997).

The value of w_t is affected by the decision variables in **u**. Poor husbandry may result in algal build-up in the cage and will reduce the nutrition available from photosynthesis, due to shading, and from filter-feeding, due to restricted water flow. The effect of husbandry is captured through a ‘husbandry effect’ (*HE*), which is a multiplier on energy intake:

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

The biological model was incorporated into a nonlinear least-squares routine and the parameter a_H (Table 2) was estimated from field data gathered by ICLARM over a period of two years in 12 sites. The dataset contained over 8,000 observations.

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

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

where CA is the cage area (cm^2), and MA is the fully projected mantle area of the clam (cm^2) which is described by:

$$MA_t = a_M w_t^{b_M} \tag{17}$$

The parameters in this function were estimated based on published reports (Klumpp and Griffiths 1994; Griffiths and Klumpp 1996). Both *HE* and *DE* are constrained to the interval (0,1); under ‘ideal’ management (ie., excellent husbandry and frequent thinning) both multipliers will have a value equal to unity. Less than ideal management will reduce their value below unity and w_T will be correspondingly affected upon numerical integration of the model.

Model Implementation

The model was implemented based on selected step price functions (Figure 1) and assuming average temperature and solar radiation cycles for the region. Parameter values and other assumptions are presented in Tables 1 and 2. The information required to estimate these parameters was collected by the senior author while on field research with ICLARM in Solomon Islands during 1997.

The initial seed weight (w_0) and number of seed-clams per cage (N) were maintained constant, while the other two decision variables (H and TF) were allowed to vary. The optimal cycle-length was estimated for a single harvest by maximising equation (7) with respect to T, while the optimal solution for the infinite horizon was estimated by maximising:

$$p_T = V_T\{h_T, \mathbf{u}, \mathbf{p}\}\frac{1}{e^{rT} - 1} \tag{18}$$

A 5×4 factorial design with five levels of H (1,...,5) and four levels of TF (3,6,12 and 18 months) was used. Results were compared based on optimal cycle-length (T^*), maximum profit obtained (p^*) and optimal labour usage (L^*).

Results and Discussion

Single-cycle case

The model was initially solved for a base case with excellent husbandry (H=5) and six-monthly thinning (TF=6) over a period of five years. This was considered to be long enough to capture the optimal cycle-length. The present value of profits from harvesting at any time during the period are presented in Figure 2A. This is a plot of the objective function given by equation (7). The shape of the function is due to the step-wise nature of discounted revenues and costs (Figure 2B), which in turn are determined partly by step-wise price functions (see

Figure 1).

Because the profit function is not continuously differentiable, it is not possible to solve for the optimal cycle-length using the Fisher rule (equation (2)). The optimal cycle-length can be established by evaluating the plot of the objective function. For the base case, T^* is after 3.21 years when the present value of profits is SBD$1,963. This corresponds to the maximum point on the graph in Figure 2A.

Solving the optimal cycle-length model for selected combinations of the decision variables *H* and *TF* gives a look-up table for optimal cycle-length in the single-cycle case (Table 3). Thinning frequency did not affect the optimal cycle-length. This is because the value of the density effect (equation (16)) was equal to one throughout the model runs.

Multiple-cycle case

Equation (18) was applied to estimate the infinite time-horizon problem. The present value of profits over time for the base case considered above and for poorer husbandry (*H*=3) are presented in Figure 3. The optimal cycle-length for the base case is now only 1.08 years, compared to 3.21 years for the single cycle. For poorer husbandry, T^* is 1.42 years. These points correspond to the maximum points on the graphs in Figure 3, where the present value of profits are SBD$20,456 and SBD$15,507 respectively.

A look-up table for optimal cycle-length, present value of profits and labour usage in the multiple-cycle case for the 20 combinations of the decision variables *H* and *TF* is presented in Table 4. The optimal cycle-length decreases with increasing husbandry and the present value of profits is highest when thinning is least frequent (at *TF*=18).

As explained above, the optimal cycle-length should be shorter in the multiple-cycle case, so long as the opportunity cost of delaying the harvest, in optimal decision rule (5), is positive. The expected results were obtained at husbandry levels of two and above, where T^* under multiple-cycle management was, on average, only 36 percent of T^* under single-cycle management (see Figure 4). When reseeding is possible, it is optimal to harvest at shorter intervals. The single-cycle solutions therefore overestimate the optimal cycle-length for each combination of the decision variables because the opportunity cost (ie., the productive value of the site) is not taken into account.

At a husbandry of one, the growth of the clams is so poor that the opportunity cost of delaying the harvest is practically zero. Clams are harvested as soon as they reach marketable size in both the multiple-cycle and the single-cycle cases. Thus, when H=1, T^* is virtually equal in both cases (Figure 4).

At any given thinning frequency, labour usage increases as cycle-length decreases (Table 4), indicating that labour and time are substitute inputs in production. A plot of average labour usage at each husbandry level against optimal cycle-length (Figure 5) illustrates this clearly. The slope of this curve means that, under optimal management, time from seeding to harvest can be decreased by 0.06534 years (23.8 days) for each additional hour of labour used per cage seeded per year.

Concluding Remarks

This study has investigated the optimal cycle-length in giant-clam farming. The results of simulation modelling suggest that maximum profits are achieved with excellent husbandry and very infrequent thinning. This is when the 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. Village farmers may not be profit maximisers however, and labour spent on giant-clam farming takes them away from other activities. Labour and cycle-length are substitute inputs in production however, so the village farmer with other objectives, will be able to produce a given level of output by using less labour and a longer cycle-length, and devote time to other activities. The paper also shows that, although the traditional forestry model provides a solid theoretical base to the optimisation model, its direct application is not possible because of the step-wise nature of clam prices and seed costs.

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Table 1. Labour requirements for giant-clam farming

Activity (i)	Labour requirement (L_i)	Units
Seeding	0.5	hrs/cage
Cleaning	$0.0036H - 0.0036$	hrs/day/cage
Thinning	0.025	hrs/clam
Harvesting	0.05	hrs/clam

Table 2. Model Parameters

Parameter	Value	Units	Parameter	Value	Units
Assumptions:			*Economic:*		
CA	5,005	cm^2	r	0.06	-
N	200	clams/cage	X_r	0.25	US$/SBD$
w_0	0.0538	g	P_L	1.50	SBD$/hr
Biological:			P_K	43.38	SBD$/cage
a_H	0.0185	-	P_M	0.95	SBD$/kg
a_M	8.3754	cm^2			
b_M	0.6392	-			

Table 3. Optimal cycle-length (T*, years) for the single-cycle case.

TF (months)	Husbandry (scale)				
	1	2	3	4	5
3 to 18	2.71	4.36	3.86	3.45	3.21

Table 4. Optimal cycle-length, maximum profit obtained and optimal labour usage for multiple-cycle case.

TF (months)	Husbandry (scale)					
	1	2	3	4	5	Mean
	Optimal cycle-length (T*, years)					
3	2.75	2.33	2.00	1.75	1.58	2.08
6	2.75	1.67	1.42	1.25	1.08	1.63
12	2.75	2.33	2.00	1.75	1.58	2.08
18	2.75	2.33	2.00	1.75	1.08	1.98
Mean	2.75	2.17	1.86	1.63	1.33	
	Maximum discounted profit (p*, SBD$)					
3	8,871	10,261	11,871	13,533	14,929	11,893
6	8,871	11,449	15,508	17,634	20,456	14,784
12	11,780	14,005	16,482	19,551	21,695	16,703
18	12,147	14,458	17,014	19,577	22,058	17,051
Mean	10,417	12,543	15,219	17,574	19,785	
	Optimal labour usage (hr/cage/year)					
3	5.5	20.6	33.6	44.3	53.2	31.4
6	5.5	12.8	16.0	19.3	22.1	15.1
12	5.2	8.6	11.1	13.1	15.4	10.7
18	4.7	7.4	9.8	11.9	14.9	9.7
Mean	5.2	12.3	17.6	22.1	26.4	

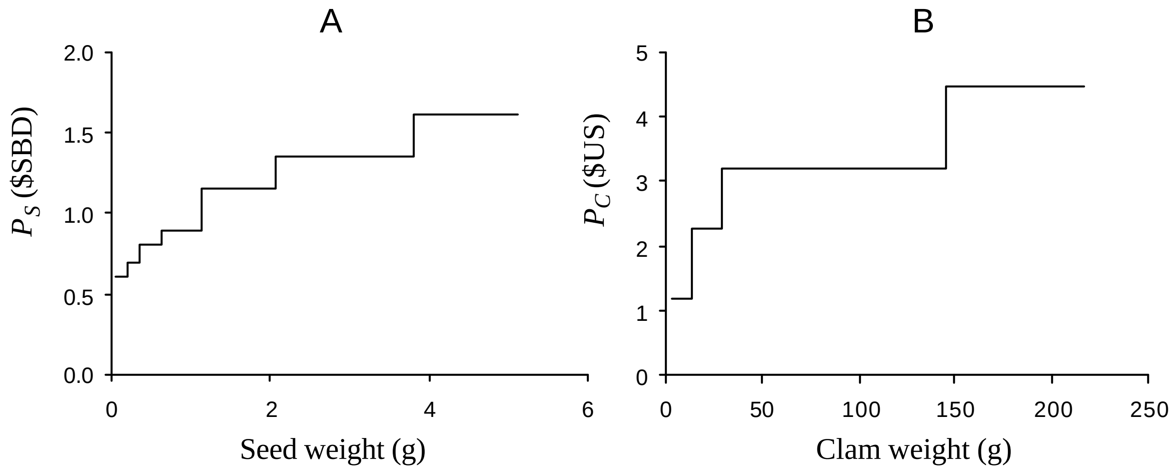

Figure 1. Step price functions for seed (A) and marketable clams (B).

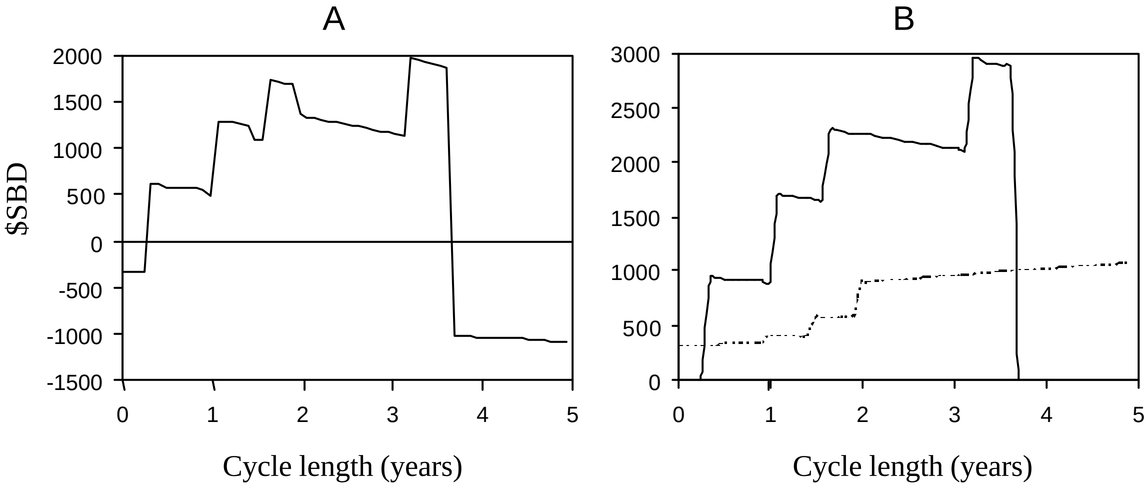

Figure 2. (A) Present value of profits and (B) present value of revenues (solid line) and costs (dotted line).

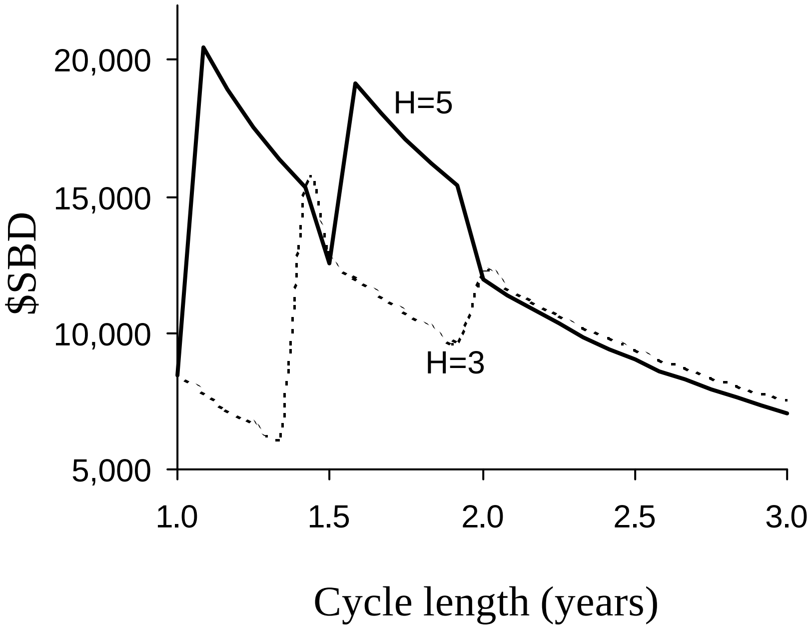

Figure 3. Present value of profits at two different husbandry levels.

Figure 4. Optimal cycle-length for the single-cycle case (dotted line) and for the multiple-cycle case (solid line) for six-monthly thinning (*TF*=6).

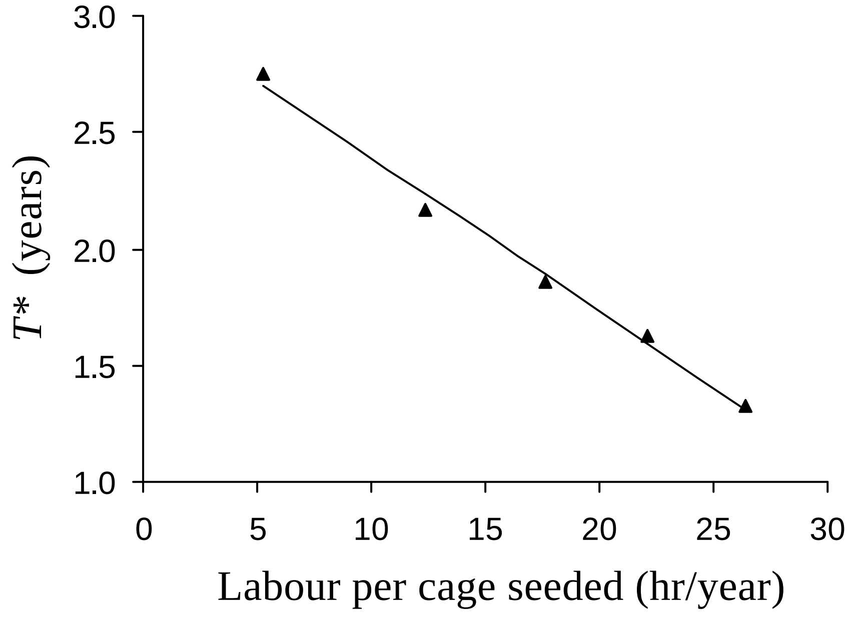

Figure 5. The relationship between cycle-length and labour usage in the multiple-cycle optimisation.