OPTIMAL BATCH LENGTHS FOR BARRAMUNDI FARMING UNDER SEASONAL VARIATIONS: A DYNAMIC PROGRAMMING APPROACH

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ABSTRACT

Key decision variables in aquaculture management are stocking level, feeding schedule, temperature control and batch length. In many management problems with an infinite planning horizon, the aim is to find the batch length which results in maximum return if the same batch length applies to all future batches. This may be an optimal strategy if all environmental and economic parameters are the same for all time periods, but not necessarily otherwise. The optimal sequence of possibly variable batch lengths for an infinite sequence of batches is determined for a barramundi farm in Port Stephens in New South Wales, Australia. This serves as a case study, in which there is seasonal variation in fish price and outside temperature. The problem is formulated and solved using dynamic programming. The extent to which the net present value of returns is increased by allowing batch length to be variable instead of fixed over an infinite planning horizon is evaluated.

Keywords: optimal harvesting, barramundi, seasonal variation, dynamic programming

INTRODUCTION

Various approaches have been used for obtaining optimal solutions to aquaculture problems based on bioeconomic models [1,2,3]. Many optimal harvesting problems reported in the literature have assumed a fixed-batch-length strategy [4,5,6,7]. However, it may be more profitable to harvest fish in a sequence of batches of different lengths. This is likely to be the case if there are seasonal variations in profit parameters such as fish price and water temperature, and batch length is not constrained to integer numbers of years.

Barramundi (*Lates calcarifer*) is a fish native to Australia and grown in marine as well as freshwater environments. Different production systems such as cage farming in sea water and fresh water, pond culture, and indoor as well as outdoor recirculation systems have been adopted by barramundi farmers in Australia. Among the different systems, the indoor recirculation system has the advantage of some control over environmental factors, such as seasonal changes in environmental temperature.

The optimal temperature for farming barramundi depends on both the growth response to water temperature and on the costs of warming and cooling water. Up to a temperature of 29˚C barramundi growth increases with water temperature. Beyond 29˚C, production suffers[b] [8]. Whether a temperature of 29˚C is an optimal target temperature depends on the costs of changing water temperature, and the need to protect the fish from heat stress. Preliminary analysis of these factors suggests that 29˚C is at least a near-optimal target temperature.

Most of the key decisions in barramundi farming are made on a weekly basis, such as feed composition and levels, culling to maintain stocking density. Consequently, batch length can be given in weeks. Since barramundi fingerlings are available all year round, and many production inputs and environmental factors can be controlled throughout the year using indoor water recirculation systems, farmers can continually stock and harvest their fish stocks. Therefore, it is assumed that barramundi farmers are interested in determining optimal batch lengths in weeks into the indefinite future.

Optimal fixed and variable batch lengths are determined for a commercial case-study farm in Port Stephens in New South Wales, Australia, where barramundi is grown in an indoor water recirculated system, in conjunction with hydroponic lettuce production in a glasshouse. Outside temperature and fish price are seasonal. The aim is to determine the extent to which the optimal variable batch schedule dominates the optimal fixed batch schedule. The problem is an integer programming problem, which is formulated and solved as a dynamic programming (DP) problem.

THE BIOECONOMIC MODEL

The bioeconomic model comprises a biophysical model, which describes the biological processes of the fish, and an economic model, which describes the cost and returns of barramundi farming. The biophysical model consists of different sub models, used to estimate growth, survival and effluent production of barramundi from stocking through to harvest under different production environments and management decisions, including batch length. The net present values of profits from the results of the biophysical model are determined for batches of different length in the economic model. The DP model and the solution procedure are given below.

Dynamic Programming Model

The DP problem is to identify the optimal infinite sequence of time lengths of batches of barramundi, allowing for seasonal market prices, and seasonal outside temperatures. The DP decision system needs to be formulated in terms of: all the possible states of the system at the start of each decision stage; the state-dependent decision (batch length l in weeks) to be made at each stage, and the resulting stage returns and state transitions. Because the selling price of barramundi and outside temperature are seasonal and have a significant impact on the net returns of a batch of barramundi produced, the state of the system is described by the calendar week i in which batch production starts, with i taking any value between 1 and 52 . Bioeconomic analysis showed that the optimal feeding level was feeding to appetite, which means that feeding level is not a decision variable.

The batch length decision l, together with the calendar week i, determine the selling price of barramundi and the costs of temperature control and hence batch returns. The start calendar week j of the following batch is given by the transition function:

$$j\{i,l\} = \begin{cases} 52 & \text{if } (i+l) \bmod 52 = 0 \\ (i+l) \bmod 52 & \text{otherwise} \end{cases} \tag{1}$$

where $(i+l) \bmod 52$ is the remainder of $(i+l)$ divided by 52.

Stage Return

Stage return $a\{i,l\}$ is the present value of net returns from producing a batch of barramundi over *l* weeks starting in week *i*:

$$a\{i,l\} = \frac{P\{W\{l\}, j\{i,l\}\}N\{l\} - \sum_{h=1}^{l} C\{h, j\{i,h-1\}\}\left(1+r_w\right)^{l-h+1}}{\left(1+r_w\right)^{l}} \tag{2}$$

Where:

l	= Batch length (the number of weeks from stocking to harvest),
$P\{W, j\}$	= Price of fish in week $j = j\{i,l\}$ for fish sale weight *W*,
$N\{l\}$	= Number of the fish at harvest,
h	= Week number of the batch process,
$C\{h, j\{i,h-1\}\}$	= Production cost incurred in the *h*-th batch week in calendar week $j\{i,h-1\}$,
r_w	= Weekly discount rate $=\left(1+r\right)^{1/52}-1$ for annual discount rate *r*.

Problem Definition

The objective of the DP model is to maximize the discounted net return over an infinite planning horizon with respect to the length of each of the infinite batches. Subscript *t* is used to index the batches. The problem is:

$$\underset{l_1,l_2,\ldots}{Max} \sum_{t=1}^{\infty} a\left\{i_t, l_t\right\} / \left(1+r_w\right)^{\sum_{s=1}^{t} l_{s-1}}$$

$$\text{subject to} \quad i_{t+1} = j\{i_t, l_t\} \quad t = 1, 2, \ldots \tag{3}$$

$$i_1 = \text{start week of the first batch (given)}$$

$$l_0 = 0$$

Where:

$a\{i_t,l_t\}$	= Present value of the net returns from the batch of length l_t starting in calendar week i_t,
t	= Stage (or batch) number,
l_t	= Length in weeks of batch starting in calendar week i_t.

Note that because the stage interval is the decision variable, the present value of *t*-th stage return in (3) is the stage return given by (2) discounted using the weekly discount factor raised to the power of the number of weeks from the start of the first batch to the start of the *t*-th batch.

DP Solution Procedure

The basis for solving the problem is the fundamental recursive functional equation of DP. It is assumed that the stage return $a\{i,l\}$ in (2) is the same for all stages *t*, which means that technical functions and all prices and costs for start week *i* and batch length *l* are the same for all batch stages. This simplifying assumption of stationarity results in the optimal *l* for start week *i* (referred to as the optimal state-dependent policy $l^*\{i\}$) is the same for all batch stages.

Denoting $V\{i\}$ as the present value of net returns from applying the optimal batch-length policy $l^*\{i\}\ \forall i$ from week *i* to all future batches $t\ (\forall t)$, it follows from (3) that the recursive functional equation (4) can be written for $V\{i\}$ at stage *t* in terms of $V\{i\}$ at stage *t*+1 on the RHS. That is, the present value of returns for any start week *i* over infinite production batches of optimal length is the present value of returns from the current batch $a\{i_t, l_t^*\}$, plus the present value of returns for the next start week $j\{i_t, l_t^*\{i_t\}\}$ over infinite production batches, discounted over $l_t^*\{i_t\}$ weeks. This generalizes to:

$$V\{i\} = \underset{l}{Max}\left[a\{i,l\} + V\{j\{i,l\}\}/(1+r_w)^l \right] \qquad i = 1,\ldots,52 \tag{4}$$

The stationarity assumption results in $V\{i\}$ being independent of *t*, and makes it straightforward to use (4) to find l^* for all *i* numerically. The $V\{i\}$ function on both sides of (4) is the same because the optimal values are for the same infinite planning horizon. The batch stage index *t* can be dropped from the equation.

The DP recursive functional equation (4) was solved numerically to obtain the optimal infinite-stage batch-length policy $l^*\{i\}$, using the latest version of the General-Purpose Dynamic Programming (GPDP) package[a]. Because GPDP normally takes the stage interval as the same for all stages, and therefore any stage discount factor as the same for all stages, minor modifications were made to GPDP in order to solve the variable batch-length problem for positive rates of discount

TECHNICAL DATA

Production Unit

Production data apply to the case study farm in Port Stephens in New South Wales. The whole fish farm is an indoor system, which has several separate recirculation production units in a greenhouse. The optimal management analysis is conducted for a water recirculation system consisting of one fibreglass production tank and other facilities such as a filtering system, PVC water recirculation pipes, and motors required for the system. The water capacity of the production tank is 10 m^3 (10,000L).

Farming begins with the introduction of fingerlings into the tank. Fish are kept in the same tank until harvest, while maintaining the recommended stocking density through mortality and culling (See Table 1 for recommended stocking densities by weight category). Culling is undertaken weekly to enable remaining fish to grow and stay healthy. Water is recirculated through the filter system and 10 per cent of the water is replaced every day.

Biophysical Data

Biophysical variables affect the barramundi yield and hence the profitability. Biophysical information includes growth, survival and environmental information. Weekly growth in fish weight depends on the food conversion ratio (FCR) and feed intake (FI) as follows:

$$W_{h+1} = W_h + \Delta W_h \tag{5}$$

$$\Delta W_h = \frac{FI\{W_h\}}{FCR\{W_h\}} \tag{6}$$

Where:

h	=	Week number of the batch process
W_{h+1}	=	Weight at start of week $h+1$ (g),
ΔW_h	=	Weight gain over period *h* to $h+1$ (g),
$FI\{W_h\}$	=	Feed Intake over period *h* to $h+1$ (g),
$FCR\{W_h\}$	=	Food Conversion Ratio over period *h* to $h+1$,

FCR values as a function of fish weight are given in Table 1. The maximum daily feed intake (DFI) by a barramundi fish is given by Williams and Barlow [8] as:

$$\ln DFI = -3.543 + 0.486 * \ln W + 0.074 * FF + 0.083 * T \tag{7}$$

Where:

DFI	=	Daily feed intake (g),
W	=	Fish weight at start of week (g),
FF	=	Feeding frequency (number of feeds per day),
T	=	Water temperature (^{0}C),
FI	=	Weekly feed intake = *DFI*7* (g).

Stocking Density

Barramundi farmers in Australia maintain stocking densities between 15 kg and 45 kg of fish per m^3 of water [9]. A search of the literature on barramundi failed to find any functional relationship between fish mortality and stocking density. As recommended by Australian state fisheries authorities, farmers maintain the maximum stocking density consistent with no adverse impact on fish growth and mortality. The maximum stocking densities used for the different weight categories in the present study are shown in Table 1**.**

Survival Data

It is assumed that water quality is maintained at the optimal level and the stocking density is maintained below or the same as given in Table 1 to avoid adverse effects. The survival rates of fish on the basis of their weight were obtained from the case-study farm and weekly mortality rates estimated from that data are presented in Table 1. On the basis of the weeks taken to achieve a given weight, survival rates are used to estimate the weekly mortality rates for different sizes of fish. In this way the number of fish at harvest ($N\{l\}$ in equation 2) is calculated.

Feasible Range of Batch Lengths

The range of feasible batch lengths to be considered in the optimisation process is bounded by the range of marketable fish weights 300g to 2kg. The range of feasible batch lengths also depends on the rate of weight gain over time, which in turn depends on the following three decision variables: the percentage of maximum feed fed, the initial batch stocking rate, and water temperature. The optimal fixed batch length for the infinite planning horizon problem and corresponding net present value was determined for all possible combinations of the three decision variables [10]. The combination resulting in maximum net present value was: feeding to 100 per cent of maximum feed, an initial batch stocking rate of 900 fingerlings per tank; and a water temperature of 29˚C. It seemed reasonable to suppose that the same combination is optimal or nearly optimal for the variable batch length problem. Consequently the same combination was used for determining the range of feasible batch lengths corresponding to the range of feasible marketable fish weights.

Table 1: Barramundi Biological and Economic Parameters

Parameter	Value	Source
Biological parameter		
Food Conversion Ratio		[8]
Fish weight <= 100g	0.9	
100g < fish weight <=200g	1.0	
200g < fish weight <=400g	1.1	
400g < fish weight <=800g	1.1	
Weekly mortality rate		Estimated from the survival rate data of the case study farm.
Fish weight <= 100g	0.00878	
100g < fish weight <=200g	0.00878	
200g < fish weight <=400g	0.00855	
400g < fish weight <=800g	0.00168	
Stocking densities (kg/m^3)		[8]
Fish weight <= 200g	15	
200g < fish weight <=400g	26	
400g < fish weight <=800g	35	
Fish weight > 800g	45	
Economic parameters		
Feed unit cost ($/kg)		[11]
Fish weight <= 100g	1.35	
Fish weight > 100g	1.15	
Water unit cost ($/$m^3$)	0.7	[Endnote c]
Fingerlings unit cost ($/fingerling)	0.8	Commercial hatchery Pers. Comm.
Electricity unit cost ($/kWh)	0.15	[10]

ECONOMIC DATA

The economic variables affecting barramundi culture profitability include production costs and barramundi prices. Overhead expenses are assumed to be constant over time and therefore do not enter the analysis. The production cost in the *h*-th week of the batch started in calendar week *i* is made up of costs of fingerlings (week 1 only), feed, temperature control and water. Economic data are given in Table 1. The following subsections describe the data and estimated procedure of sales revenue and various production costs.

Barramundi Price and Sales Revenue

Sales revenue equals the product of harvest (kg) and unit price of barramundi ($/kg). Barramundi farmers in Australia sell their production to local restaurants under contract sales agreements or sell through wholesale fish markets at Melbourne or Sydney. The prices received from local restaurants are not readily available and have to be obtained through personal communication. To sell to the restaurants, fish have to be the right size to fulfill the buyers' requirements. The present study did not use the contract price or price received from local restaurants.

Wholesale prices for fresh farmed barramundi for the four years 1999 to 2002 at the Sydney Fish Market were the basis of the market prices in this study [12]. Prices for each week of each year were adjusted to the base year (1999) and then averaged. The average price of barramundi varies with the weight of the fish as well as on the calendar week of the year. The changing pattern of price over a year is shown in Figure 1 for small and large weight categories. Prices are higher over the December to January period, as well as over weeks 37 to 45. Low prices prevail in the middle of the year.

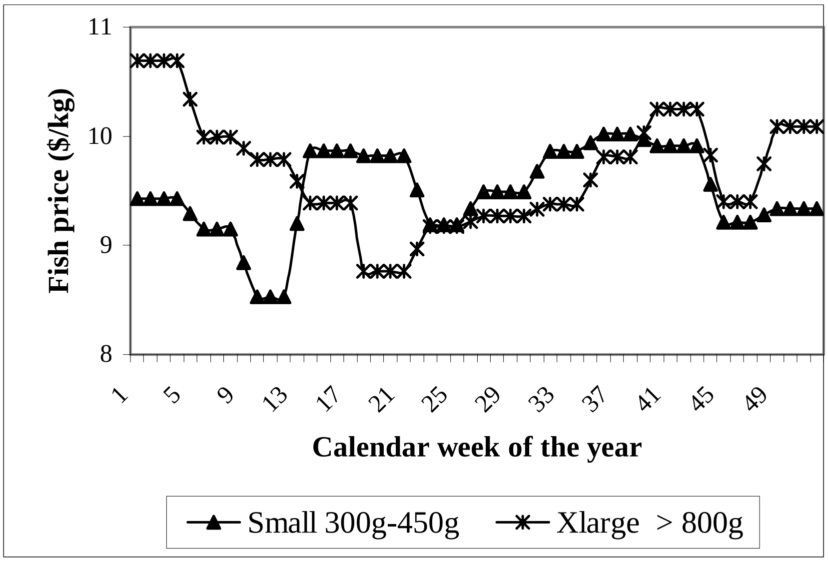

Figure 1. Weekly variation of barramundi price for different weight categories
(Data source: Sydney Fish Market [12])

Price of Fingerlings

Data relevant to the price of fingerlings were obtained from two commercial barramundi hatcheries. The initial size of fingerlings for this study is taken to be 7 g, with a length of approximately 80 mm. Both hatcheries quoted prices of 80 cents for fingerlings of this size.

Price of Feed and Feed Cost

The amount of feed and hence feed cost per week depends on the fish weight, FCR, feed wastages, and the price of different feed types. Feeding frequency is twice a day until the fish reach the weight of 100 g and feeding once a day beyond that size. The total feed cost per week equals the product of the number of fish and feed cost per fish. The feed cost per fish is calculated as the product of feed requirements and the price of feed.

Though there are different feed categories for different size of fish, all feed categories contain almost the same protein percentage (45-50 per cent). However, as size of the feed particles is different in different feed categories, price of feed is also different for different feed categories. The prices of different feeds for different weight intervals are given in Table 1.

Cost of Water

Water has to be exchanged daily from the day of fish release until the day of harvesting. The rate of daily water exchange is 10 per cent of the total water volume. The cost of water consists of the cost of the initial volume of water in the tank and the cost of the volume of exchange. The total cost of water per week is the product of the total volume of water required per week and the unit cost of water. The unit cost of water is taken to be \$ 0.7 per m^3.

Water Temperature and Cost of Water Heating

On the commercial farm, no system is used to directly heat or cool the tank water. Tank water temperature depends on outside temperature, and as a result of water recycling, the temperature in the greenhouse where the lettuce are grown, moderated by manipulation of roof blinds. The question of whether directly heating or cooling tank water was investigated [10]. Average weekly water temperatures for the farm in 2002, based on the daily average temperatures, were taken as indicative of the annual seasonal variation in tank water temperature without direct control.

Because higher water temperatures lead to increased fish appetite, greater feed intake and higher growth rates (Equations 6 and 7) up to 29^0C, and feeding to appetite was found to be profitable, raising tank water temperature to 29^0C may be economic. Given that the maximum uncontrolled temperature in 2002 was 28^0C, direct cooling of the water is unnecessary. A temperature of 29^0C would be maintained through heating the water in all weeks. If a lower target temperature of say 27^0C were chosen, heating would only be necessary in those weeks with water temperature less than 27^0C. Profitability would be greater in weeks with water temperature above 27^0C. Thus the target water temperature is best described as a minimum target water temperature (MTWT) across all weeks.

The weekly cost of heating is the product of the weekly energy requirement and the unit price of electricity. The method used for calculating the energy required to raise water temperature from t_0 to t' is detailed by Rupasinghe [10] The unit price of electricity is 15 cents per kWh, approximately the average for the farm business category.

Discount Rate

Determining the appropriate rate of discount for a particular investment project is a debatable issue. Governments usually set the minimum real rate of return that should be generated from public investment and that value can be used as the base rate. Six per cent to 10 per cent discount rates have been used in the economic analyses relevant to aquaculture projects in Australia. Hinton [13] used an 8 per cent discount rate in a cash flow analysis to determine the profitability of barramundi farming. To analyse the economics of recirculation aquaculture for a 10 year planning horizon, Rawlinson and Foster [14] also used an 8 per cent discount rate. Johnston [15] employed a discount rate of 8 per cent for the cash flow analysis in barramundi farming. Dalton [16] used a 10 per cent discount rate for the economic feasibility analysis of integrating a fish production system into a dairy farm processing system. For the base case of the present study an 8 per cent discount rate is applied.

RESULTS AND DISCUSSION

The optimal results of the DP model for the case study farm show that for parameter values of maximum ration (Rmax), target water temperature 29^0C, and initial stocking density of 900 fish per tank, starting in calendar week 1, the optimal sequence of batch lengths is 21 weeks followed by 31 weeks. This sequence is repeated indefinitely, revisiting start weeks 1 and 22 continually, resulting in a present value of net returns (PVNR) of $85,571. The corresponding optimal fixed batch length of 30 weeks implemented across an infinite planning horizon results in a $PVNR^d$ of $79,782, a fall of 7 per cent.

The main rationale for the variable batch length solution of harvesting always in calendar weeks 21 and 52 is that the price of barramundi is relatively high in these weeks ($10.17 per kg and $10.09 per kg respectively) for final weights of 635 g and 1,180 g respectively. Natural water temperature in tanks is at its highest level around week 52, close to 29^0C, although at week 21 it is close to its lowest level.

Sensitivity to the Calendar Week of First Stocking

The optimal batch length cycle of 21 weeks followed by 31 weeks, starting in calendar weeks 1 and 22 respectively, is eventually reached whatever the calendar week in which operations start. The number of batches before reaching the optimal cycle, and the associated PVNR, depend on the start week. For example, when the first stocking week is 1, the optimal cycle is reached at the third batch, whilst starting at week 9 it is not reached until the eighth batch. The results for five start weeks are given in Table 2: weeks 1 and 48 fall in summer, and weeks 9, 22 and 35 fall in autumn, winter and spring respectively. The PVNR is not sensitive to the start week.

Sensitivity to the Minimum Target Water Temperature (MTWT)

Water temperature was not included as a decision variable for the DP problem since preliminary analysis indicated that 29^0C was optimal for any batch. However, it is important to investigate the optimal sequence of batch length when the MTWT is changed. The results in Table 3 show that the optimal batch length is sensitive to MTWT. The optimal batch length decreases and the PVNR increases as MTWT increases. Fish reach marketable size sooner, with higher feed intake and growth of fish.

Table 2: Optimal Sequence of Batch Length and PVNR for Infinite Batches of Different Calendar Weeks of Stocking* (Decision combination: Rmax, 900 fish and 29^{0}C)

	Optimal batch length sequence (weeks)				
	Stocking calendar week				
Batch No.	1**	9	22	35	48
1	21	32	34	21	21
2	34	28	**21**	**21**	37
3	**21**	37	**31**	**31**	21
4	**31**	21			32
5		32			21
6		21			32
7		32			**21**
8		**21**			**31**
9		**31**			
PVNR ($)	85,571	85,342	85,855	85,534	85,589

* Bold numbers represent the optimal sequence eventually reached and repeated indefinitely
** Base case results

Table 3: Effect of changes in TMWT on Optimal Sequence of Batch Length and PVNR for Infinite Batches* (Decision combination: Rmax and 900 fish)

	Optimal batch length sequence (weeks)						
	Target minimum water temperature (^{0}C)						
Stage No.	23	24	25	26	27	28	29**
1	53	54	42	40	42	22	34
2	**52**	**52**	**26**	**25**	**24**	33	**21**
3			**39**	**40**	**40**	**39**	**31**
4			**50**	**39**	**40**	**26**	
5			**41**			**37**	
6						**22**	
7						**32**	
PVNR ($)	65,397	66,015	67,100	68,931	73,144	78,780	85,571

CONCLUSION

The results of the dynamic programming model show that harvesting batches of barramundi over optimal lengths of time can be significantly more profitable than harvesting at optimal fixed intervals. This applies for the annual seasonal variation of barramundi price and water temperature on the case-study farm. Whatever the calendar start week, the same perpetual annual two-batch cycle was eventually reached. The number of non-cycle batches before the perpetual cycle was reached depended on the start week. The present value of net returns from start week across infinite batches was little affected by the start week.

The results suggest that aquaculture managers may benefit from identifying seasonal variation in biological, economic and environmental variables, and taking account of them in managing the farmed fish stock. Dynamic programming has been shown to be a suitable technique for determining the optimal strategies for exploiting seasonal variations in relevant variables. The approach demonstrated in this paper could be extended to allow for stochastic factors such as weekly fish growth or unexpected outbreak of disease causing a planned batch to be prematurely terminated.

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ENDNOTES

a. The current version is Windows-based. The data file required to solve a DP problem can be generated from a DP problem Workbook with a Visual Basic routine, modifying template routines for entering all the component problem data. A file for installing GPDP, a manual [17]. and the DP book by Kennedy [18] can be downloaded from: http://www.business.latrobe.edu.au/public/staffhp/jkennedy/index.htm

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d. The optimal fixed batch length was found by total enumeration of all possible batch lengths. The optimal length was the length for which the present value of net revenues across infinite batches was maximised.

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