ABARE CONFERENCE PAPER 2001.7

Specification of length of planning period and terminal value of fish stock

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45th Annual Conference of Australian Agricultural and Resource Economics Society
Stamford Plaza Hotel, Adelaide
23-25 January 2001

Abstract

In a dynamic bioeconomic multicohort analysis of fishing for a long lived species there can be a terminal value problem. The way this problem is dealt with can have a significant bearing on optimal policy recommendations derived from the model.

In this paper, a bioeconomic model of the southern bluefin tuna fishery is specified to determine optimal harvests over planning periods of different length. In each case zero prices were assumed for fish stocks left over. It was confirmed that the harvest levels that maximise the economic rent can be affected if the planning period chosen for the model is not long enough to make the influence of the assumption of zero prices for leftover stocks negligible. Model parameter values, initial stock conditions and the policy controls all can have a significant influence on the choice of an appropriate length of the planning period.

Apart from increasing the length of the planning period while maintaining the assumption of zero prices for leftover fish stocks, positive price estimates for leftover fish stocks can be used to provide terminal conditions on prices of leftover fish stocks.

ABARE Project 1820

Introduction

One of the objectives of bioeconomic analysis of fisheries is to find the optimal management policy to maximise the net benefits over the planning period. In some bioeconomic models it is assumed that fish left over at the end of the planning period have no value (for example, Kennedy 1999 and Kennedy, Davies and Cox 1999). This assumption can lead to optimal exploitation rates that initially are higher than under positive values for leftover fish, in particular when the planning period is short. This assumption also implies that the choice of the length of the planning period can affect the optimal management policy, especially for long lived species such as the southern bluefin tuna. The questions are then, what length of planning period should be used in a bioeconomic analysis for a particular fishery and how fish should be valued at the end of the planning period?

For a sufficiently long planning period, an assumption that fish have no value at the end of that period, may have no effect on harvests early in the planning period. However, the use of a planning period long enough to make the influence of this assumption negligible may cause computational problems in practical applications. Most existing algorithms for optimisation are not capable of solving systems of large dimension. However, solutions found for a short planning period with zero values for leftover fish stocks may be far from optimal for long lived species such as the southern bluefin tuna.

The use of positive terminal values of fish in optimisation problems with a shorter planning horizon is considered as a solution to the computational problems associated with optimisation problems with a longer planning horizon which is often required in the bioeconomic modeling of a long lived species. Three approaches to specify terminal values of fish are tested. The southern bluefin tuna fishery is taken as an example to illustrate the use of positive terminal values of fish for a joint rent maximisation problem over a range of lengths of the planning period. The results presented in this paper should not be used to analyse current or future policies in the Southern bluefin tuna fishery.

Southern bluefin tuna fishery

Description of the fishery

Southern bluefin tuna (SBT) is a slow growing and highly migratory species, forming a single widely distributed stock in the southern ocean. The spawning ground between Java and northern Western Australia is visited between September and March each year. The fish are long lived and slow to mature. They reach maturity at around eight years, but live for as long as forty years and grow to about 200 kilograms in weight and 200 centimetres in length.

Juveniles of the fish tend to move south from the spawning ground to waters off the south west of Australia in the first several years of life. Some then move westward, but most move east within Australian coastal and continental shelf waters. Southern bluefin tuna continue to live off southern and south eastern Australia until six to nine years of age. By maturity, most of the fish have dispersed into the deeper waters of the south Atlantic, Indian and south west Pacific Oceans. Over the summer months, juvenile fish are taken in the Australian surface fishery by purse seine and pole and line techniques. Over half of the annual catch is taken by longlining by Japan, the Republic of Korea, Indonesia and Chinese Taipei as vessels follow oceanographic conditions.

The stock is fished primarily by Japan, Australia and New Zealand, and to a lesser extent by the Republic of Korea, Indonesia and Chinese Taipei. Almost all of the catch is sold in the Japanese market.

Management arrangements of the fishery

Concerns over the sustainability of the SBT fishery have been raised in recent years with the heavy decline in stock since the early 1960s and the decline in catches through the 1980s. These concerns prompted Australia, Japan and New Zealand to enter into an informal agreement in 1984 and ratify in May 1994 the formation of the Convention for the Conservation of Southern Bluefin Tuna to limit catches. The Commission for the Conservation of Southern Bluefin Tuna (CCSBT) was formed as a management body under the above convention primarily to set a total allowable catch and allocate that catch between member nations. Catch limits were progressively reduced from around 40000 tonnes in 1984 at the start of the informal management arrangement to 11 750

tonnes in 1990 and remained fixed at this level until 1997. The quota is divided between Japan (6065 tonnes), Australia (5265 tonnes) and New Zealand (420 tonnes). However, Japan, Australia and New Zealand failed to reach an agreement to set a total allowable catch and each country's share for 1998 and 1999. That was mainly due to a disagreement between Japanese scientists and scientists from Australia and New Zealand over the likely trends in stock size under the continuation of recent catch level. Japan also subsequently proposed that it should be allowed an additional catch of southern bluefin tuna under an 'experimental fishing program'.

Difficulties under the CCSBT could also be partly due to the increasing share of the total catch by non-CCSBT countries. The CCSBT members' share declined from 90 per cent in 1990 to 72 per cent in 1997. Most of the non-CCSBT catch was taken by Indonesia (2241 tonnes), the Republic of Korea (1170 tonnes) and Chinese Taipei (640 tonnes) (the catch figures in the brackets are from the catch data of 1997). In December 2000 the Republic of Korea and Indonesia agreed to join the CCSBT and to restrict their annual catches of SBT.

Bioeconomic modeling of SBT fishery

Bioeconomic models of the southern bluefin tuna fishery have been formulated by a number of researchers, including Hagan and Henry (1987), Kennedy and Pasternak (1991) and Klieve and MacAulay (1993). Evidence from these modeling studies indicates that limiting the SBT harvest can be a reasonable instrument to rebuild the stock. However, much has changed in the southern bluefin tuna fishery since these studies were undertaken. In particular, the estimate of stock status in recent years and the increasing catch by non-CCSBT countries, have added greater complexity to the ongoing efforts in negotiating alternative international management arrangements.

Kennedy (1999) and Kennedy, Davies and Cox (1999) developed a multicohort model of the southern bluefin tuna fishery to analyse the strategic interactions between the three main groups of harvesting nations: Australia and New Zealand (ANZ); Japan; and the Republic of Korea, Indonesia and Chinese Taipei (KIT). The model used in this study is similar to the models in Kennedy (1999) and Kennedy, Davies and Cox (1999)

with a few exceptions: (a) fattening of juvenile SBT in farm pens by Australia and New Zealand is included; (b) the two fishing effort variables specified in Kennedy (1999) and Kennedy, Davies and Cox (1999) are consolidated into one, and (c) positive values for the SBT stocks left over can be specified instead of zero values assumed in Kennedy (1999) and Kennedy, Davies and Cox (1999).

A bioeconomic model of the SBT fishery

The model consists of a biological and an economic component, which are linked together. The biological component captures the dynamics of growth of the multicohort fish stock while the economic component captures the behaviour of three groups of countries engaged in harvesting the stock. The model is used to determine the optimal harvest profile for each country group over the planning period.

Biological component

The biological component includes a stock–recruitment relationship and for each age class and each year the process of updating of stock considering the fishing and natural mortalities and the stock in the previous year. The model representation of the SBT fishery has *i* age classes of fish with *n* country groups planning to exploit the resource over *t* years. A detailed description of all notations used is given in Appendix A.

For the first year of the planning period (*t*=1), for each age class *i*, the number of fish at the beginning of the year, $x_i(1)$ is assumed to be equal to the 1997 stock estimated by CSIRO (Klaer, Preece, Polacheck, Miller and Jones, 1998). Stock numbers by age class in 1997 as estimated by CSIRO are given in table 1 along with other age specific parameters. For each of the years from the second year onward, $t+1$, of the planning period, the number of fish at the beginning of the year is given by equations 1 and 2 for age class 1, by equation 3 for age classes 2–20 and by equation 4 for age class 21 and over.

$$x_1(t+1) = \alpha\, s(t)/(\beta + s(t)), \tag{1}$$

$$s(t) = \sum_i sw_i\, pm_i\, x_i(t)/1000, \tag{2}$$

For each of the years from the second year onward, $t+1$, the recruitment to age class 1, $x_1(t+1)$, is a function of the spawning stock biomass, $s(t)$, in the previous year, *t*, according to the Beverton-Holt recruitment–stock relationship (equation 1). For each year, *t*, the spawning stock biomass, $s(t)$, is approximated by taking the aggregate spawning weight of all fishes of age class 9 and over (equation 2). The unit spawning weights of fish (sw_i) used in this estimation are given in table 1 and all the fishes of age class 9 and over are assumed to be sexually mature $(pm=1)$. The values used for α and β parameters in equation 1 are given in table 2.

$$x_{i+1}(t+1) = x_i(t)e^{-g_i(t)}, \qquad i=1,2,\ldots,19 \tag{3}$$

For each of the years from the second year onward, $t+1$, for each age class from 2 to 20, $i+1$, the stock at the beginning of the year is equal to the stock of one year younger (i) fish in the previous year, *t*, adjusted for the total mortality of one year younger fish in the previous year ($g_i(t)$).

$$x_{21}(t+1) = x_{20}(t)e^{-g_{20}(t)} + x_{21}(t)e^{-g_{21}(t)}, \tag{4}$$

For each of the years from the second year onward, $t+1$, for the age classes 21 and over, $i=21$, the stock at the beginning of the year is equal to the stock of fish of age class 20 ($i=20$) in the previous year, *t*, adjusted for the total mortality of fish of age class 20 in the previous year ($g_{20}(t)$) plus the stock of fish of age class 21 and over ($i=21$) in the previous year, *t*, adjusted for the total mortality of fish of age class 21 and over in the previous year ($g_{21}(t)$).

$$g_i(t) = m_i + \sum_n q_{in} f_n(t), \quad i=1,2,\ldots,21. \tag{5}$$

For each year, *t*, and for each age class, *i*, the total rate of mortality is equal to the rate of natural mortality, m_i plus the aggregate rate of fishing mortality (second term in equation 5). For each year, *t*, and for each age class, *i*, the aggregate rate of fishing

mortality is the sum over all *n* groups, the product of the selectivity coefficient, q_{in}, and the fishing effort, $f_n(t)$. The selectivity coefficients assumed, q_{in}, are given in table 1.

Table 1. Values of model parameters

Age class	1997 Stock	Spawning weight	Catch weight	Proportion mature	Natural mortality	Selectivity coefficients		
						Longline (JPN)	Surface (ANZ)	Other (KIT)
I	$x_i(1)$	sw_i	w_i	pm_i	m_i	q_{i1}	q_{i2}	q_{i3}
Yr	Number	Kg/fish	Kg/fish					
1	2354506	0.00	1.48	0	0.400	0.000	0.000	0.000
2	1479051	2.82	6.79	0	0.350	0.000	0.000	0.000
3	965190.2	9.28	15.67	0	0.300	0.003	0.028	0.001
4	683811.4	16.90	24.50	0	0.250	0.017	0.144	0.006
5	427870.9	25.10	33.98	0	0.233	0.050	0.155	0.018
6	407885	33.71	39.67	0	0.217	0.053	0.025	0.017
7	316752	43.45	49.46	0	0.200	0.054	0.007	0.018
8	222484	54.59	58.85	0	0.175	0.060	0.006	0.020
9	171906	65.42	67.59	1*	0.150	0.056	0.003	0.020
10	112124	75.63	75.57	1	0.125	0.051	0.002	0.023
11	65568	85.02	82.71	1	0.100	0.054	0.001	0.029
12	41129	93.52	89.03	1	0.100	0.056	0.001	0.040
13	14136	101.08	94.56	1	0.100	0.138	0.004	0.130
14	11239	107.74	99.36	1	0.100	0.117	0.004	0.152
15	8733	113.55	103.50	1	0.100	0.122	0.004	0.147
16	8690	118.57	107.05	1	0.100	0.121	0.002	0.149
17	5453	122.90	110.08	1	0.100	0.093	0.004	0.175
18	5373	126.60	112.66	1	0.100	0.113	0.003	0.157
19	4423	129.75	114.82	1	0.100	0.077	0.002	0.192
20	6059	132.37	116.60	1	0.100	0.124	0.001	0.147
21	52749	134.54	118.09	1	0.100	0.070	0.004	0.198

Source: Klaer *et al.* (1998) and Kennedy *et al.* (1999).

* In Kennedy *et al*. (1999), this value was zero. Based on the source data from Klaer *et al*. (1998) a more likely value is unity.

Table 2 Other parameters

Parameter	Description	Value
α, β	Recruitment function parameters	1.230E+7, 1.843E+5 *
η_{nn}	Own price elasticity of demand	-1, -1, -1 *
$\eta_{nm}(m \neq n)$	Cross price elasticity of demand	2, 2, 2
θ_n	Total cost as a proportion of total revenue in the base year	0.96, 0.80, 1.00
ρ	Total fishing cost (from ocean) as a proportion of total cost for ANZ in the base year	0.5
$h_n(1)$	Base year (ie, 1997) harvest (tonnes)	6339, 5759, 4185
$p_n(1)$	Base year price (A$/kg)	39, 22, 19 *
r	Annual discount rate	0.1
σ	Proportional weight increase in ANZ SBT farm	0.3
$f_n(1)$	Estimated fishing effort in the base year	1.176, 1.241, 1.195

* Source: Kennedy *et al.* (1999) and Kennedy (1999).

$$h_{in}(t) = \frac{q_{in} f_n(t)}{g_i(t)} x_i(t)(1 - e^{-g_i(t)}) \tag{6}$$

$$h_n(t) = \sum_i w_i h_{in}(t)/1000. \tag{7}$$

For each year, *t*, each age class *i* and each country group, *n*, the number of fish harvested, $h_{in}(t)$ is proportional to fishing effort by that country group in that year adjusted for the rate of total mortality during the year (equation 6). For each year, *t*, and each country group, *n*, the total harvest in tonnes from all age classes is given in equation 7 where w_i represents catch weight per fish (table 1).

$$o_n(t) = \begin{cases} h_n(t), & n = 1 \text{ or } 3, \\ (1+\sigma)h_n(t), & n = 2. \end{cases} \tag{8}$$

It is assumed that all of Australia's and New Zealand's catch consists of younger fish that are caught live, transferred to farm pens and fattened before harvest. The fattening

on farm by Australia and New Zealand is accounted for by adjusting the tonnage harvested by a factor of σ. For each country, the final harvest, $o_n(t)$ is given in equation 8.

Economic component

The economic component of the model includes inverse demand relationships in the Japanese market for SBT differentiated by country of origin and accounting identities for sales revenue and cost of fishing for individual country groups and consumer surplus in the Japanese market.

$$p_n(t) = a_n + \sum_m b_{nm} o_m(t), \tag{9}$$

$$b_{nm} = \begin{cases} p_n(1)/(o_m(1)\eta_{mn}), & m = 1,2,3,\ n = m, m+1, \cdots, 3, \\ b_{mn}, & \text{otherwise}, \end{cases} \tag{10}$$

$$a_n = p_n(1) - \sum_m b_{nm} o_m(1). \tag{11}$$

For each country group and each year, the price of SBT caught $p_n(t)$ is assumed to be a linear function of the harvests from all country groups ($o_m(t)$). The parameters of these inverse demand equations, a_n and, b_{nm} are estimated using the prices and harvests in 1997 and the own and cross price elasticities of demand (η_{nn} and η_{nm}, respectively) in the Japanese market given in table 2. The matrix of price coefficients (b_{nm}) satisfies the requirement of symmetry.

$$TR_n(t) = p_n(t) o_n(t). \tag{12}$$

For each country group, the total revenue, $TR_n(t)$ is given by price received for its product in the Japanese market, $p_n(t)$ times the harvest, $o_n(t)$.

$$CS(t) = -0.5 \sum_n \sum_m o_n(t) b_{nm} o_m(t). \tag{13}$$

As the total catch from all country groups is assumed to be sold on the Japanese market, in each year, *t*, all consumer surpluses, $CS(t)$, accrue to Japanese consumers.

$$TC_n(t) = \begin{cases} c_n f_n(t), & n = 1 \text{ or } 3, \\ c_n f_n(t) + c_f \sigma h_n(t), & n = 2. \end{cases} \tag{14}$$

For each country group, in each year, *t*, the total cost, $TC_n(t)$ is assumed to be linearly dependent on the fishing effort applied throughout the year by the country where c_n represents the cost of fishing per unit effort. For Australia and New Zealand, the total cost also includes the cost for fattening on farm (second term in equation 14 where c_f represents the cost of fattening per unit of weight gain).

$$c_n = \begin{cases} \theta_n p_n(1) o_n(1) / f_n(1), & n = 1 \text{ or } 3, \\ \rho \theta_n p_n(1) o_n(1) / f_n(1), & n = 2. \end{cases} \tag{15}$$

For each country group, *n*, the cost of fishing per unit effort c_n is approximated by multiplying the sales revenue per unit effort by the proportion of total cost to the total revenue, θ_n in 1997. The data on harvest, prices and the proportions of total cost to the total revenue in 1997 used in this calculation are given in table 2. For each country group, *n*, the fishing effort in 1997 was estimated by simultaneously solving equation (7) and (5) using data given in table 1.

$$c_f = (1-\rho)\theta_2 p_2(1) o_2(1) / (\sigma h_2(1)) . \tag{16}$$

For Australia and New Zealand, *n=2*, the cost of fattening per unit of weight gain c_f is approximated by the sales revenue per unit of weight gain times the proportion of total cost to total revenue, θ_2 times the proportion of the fattening cost to the total fishing cost ($1-\rho$).

$$NR_n(t) = TR_n(t) - TC_n(t) . \tag{17}$$

For each country group, *n*, the net return $NR_n(t)$ which is the difference between total revenue and total cost, is given in equation 17.

Model 1 Optimal exploitation with zero values for leftover fish stock

$$\sum_{t=2}^{T} [CS(t) + \sum_{n=1}^{3} NR_n(t)](1+r)^{1-t} \tag{18}$$

If no value is put on fish stocks left over at the end of the planning period, then the optimal harvest profiles corresponding to joint rent maximisation are obtained as the solution to the problem of maximising the objective function (18) subject to conditions (1) – (17). The objective function represents, for the whole southern bluefin tuna fishery, the sum of discounted net returns and consumer surplus over the planning period from year 2 onward (the discount rate is represented by r in equation 18). Optimal harvest profiles can also be obtained for alternative management regimes such as open access and open access with policies such as harvest quotas or export taxes or import tariffs by Japan. These management regimes are not examined in this paper.

Economic value of fish stock

An expression for the economic values of fish stocks can be derived by solving the first order conditions of the model 1. The value of a fish of age class i in year t is denoted by $\lambda_i(t)$.

$$\lambda_i(t) = \begin{cases} \dfrac{\lambda_1(t+1)}{1+r}[\alpha\psi_i(t) - x_1(t+1)\psi_i(t)] + \dfrac{\lambda_{i+1}(t+1)}{1+r}e^{-g_i(t)} + \sum_n \mu_n(t)\xi_{i,n}(t), & i \le 20, \\ \dfrac{\lambda_1(t+1)}{1+r}[\alpha\psi_i(t) - x_1(t+1)\psi_i(t)] + \dfrac{\lambda_i(t+1)}{1+r}e^{-g_i(t)} + \sum_n \mu_n(t)\xi_{i,n}(t), & i = 21, \end{cases} \tag{19}$$

where $\xi_{i,n}(t) = w_i q_{in} f_n(t)(1-e^{-g_i(t)})/[1000 g_i(t)]$, $\psi_i(t) = sw_i pm_i/[1000(\beta + s(t))]$, and $\mu_n(t) = 0$ when $t = 1$, and $\mu_n(t) = \begin{cases} p_n(t) & n = 1 \& 3 \\ p_n(t)(1+\sigma) - c_f\sigma & n = 2 \end{cases}$ when $t > 1$.

For each age under 21, i and at the beginning of each year, t, the present value of fish, $\lambda_i(t)$ equals the value for recruitment the next year (first term) plus the value for the surviving proportion at a one year older age (ie, i+1) the next year (second term) plus the value for the proportion harvested in the current year (third term).

Model 2 Optimal exploitation with <u>known</u> values for leftover fish stock

$$\sum_{t=2}^{T} [CS(t) + \sum_{n=1}^{3} NR_n(t)](1+r)^{1-t} + \sum_{i} \lambda_i(T+1)x_i(T+1)(1+r)^{-T} \qquad (20)$$

If positive values for leftover fish stock are known, then the optimal harvest profiles corresponding to joint rent maximisation are obtained as the solution to the problem of maximising the objective function (20) subject to conditions (1) – (17). The objective function in this case is similar to equation (18) except for an additional term, which represents the sum over all age classes, *i*, the discounted value of stocks left over at the end of the planning period, ($t = T$ +1). The value of a fish of age class *i* at the end of the planning period $T+1$ is given by λ_i.

The objective function (20) can be solved if the unit value of left over fish stock of each age class is known.

Model applications

As little data are available on the values of left over fish stocks, bioeconomic modeling of long lived fisheries needs to look at other avenues to appropriately specify such values. Three methods, which represent three possible applications of above models to specify appropriate values for left over fish stocks, are considered in this study. They are explained in detail as follows.

Method–I

Considering a 20 year planning period as an example, first, model 1 is run over a longer planning period, say 100 years, and the fish values at the 21st year are obtained from the shadow prices of equation (1), (3) and (4). Second, model 2 is run over a 20 year planning period assuming that the fish values obtained at the first step are equal to $\lambda_i(T+1)$. This method is not practical, as the model needs to be run over a sufficiently long planning period to obtain values for left over fish stock. However, it is included in this study to demonstrate that the more realistic harvest profiles obtained from model runs with sufficiently long planning period but with zero values for left over stocks

(model 1) can be approximated by the use of appropriate positive values for left over fish stocks in model runs with short planning period (model 2).

Method–II

Considering a 20 year planning period as an example, first, model 1 is run over a 20-year period, and the fish values at the 20th year are obtained from the shadow prices of equation (1), (3) and (4). Second the fish values obtained in this manner are used as start values in an iterative procedure with model 2. In this procedure, model 2 is solved after running it over 3 iterative steps assuming a 20-year planning period at each step.

step 1. run model 1 to calculate the <u>initial</u> current values of fish at the 20th year, $\lambda_i^0(20)$ from the shadow prices of equation (1), (3) and (4) of that model run;

step 2. run model 2 by setting $\lambda_i(21) = \lambda_i^0(20)$ to obtain the <u>updated</u> current value of fish at the 20th year, $\lambda_i^1(20)$ from the shadow prices of equation (1), (3) and (4) of that model run;

step 3. compare $\lambda_i(21)$ with $\lambda_i^1(20)$. If $|\lambda_i(21) - \lambda_i^1(20)| < 0.01$ for all ages *i*, *then the solution is achieved*; otherwise, go to step 4. Note 0.01 is a tolerance of convergence and other values may be used;

step 4. repeat step 2 and step 3 until convergence *is achieved*.

At the solution, the values of left over fish stocks are close to the fish values at the last year in the planning period within a given tolerance. This method is applicable in practical situations, but will overstate the true terminal value of the stock to some extent.

Method–III

In this method, first a static version of model 2 is formulated by dropping the time (*t*) from all the equations. Then a steady state model of the SBT fishery is formulated by adding the condition (19), after dropping the time (*t*). The steady state model is given as follows.

$$x_1 = \alpha\, s/(\beta + s),$$

$$s = \sum_i sw_i\, pm_i x_i\, /1000,$$

$$x_{i+1} = x_i e^{-g_i}, \quad i=1,2,\ldots,19,$$

$$x_{21} = x_{20} e^{-g_{20}} + x_{21} e^{-g_{21}},$$

$$g_i = m_i + \sum_n q_{in} f_n, \quad i=1,2,\ldots,21,$$

$$h_{in} = \frac{q_{in} f_n}{g_i} x_i (1 - e^{-g_i}),$$

$$h_n = \sum_i w_i h_{in}\, /1000,$$

$$o_n = \begin{cases} h_n, & n = 1 \text{ or } 3, \\ (1+\sigma) h_n, & n = 2, \end{cases}$$

$$p_n = a_n + \sum_m b_{nm} o_m,$$

$$TR_n = p_n o_n,$$

$$CS = -0.5 \sum_n \sum_m o_n b_{nm} o_m,$$

$$TC_n = \begin{cases} c_n f_n, & n = 1 \text{ or } 3, \\ c_n f_n + c_f \sigma\, h_n, & n = 2, \end{cases}$$

$$NR_n = TR_n - TC_n,$$

$$\lambda_i = \begin{cases} \dfrac{\lambda_1}{1+r}[\alpha\psi_i - x_1\psi_i] + \dfrac{\lambda_{i+1}}{1+r} e^{-g_i} + \sum_n \mu_n \xi_{i,n}, & i \le 20, \\ \dfrac{\lambda_1}{1+r}[\alpha\psi_i - x_1\psi_i] + \dfrac{\lambda_i}{1+r} e^{-g_i} + \sum_n \mu_n \xi_{i,n}, & i = 21. \end{cases}$$

The co-state variable for the steady state condition is given in the last equation. The solution of the optimal steady state can be obtained by maximising: $CS + \sum_{n=1}^{3} NR_n + \sum_i \lambda_i x_i /(1+r)$ subject to the above equations.

The steady state values of the leftover fish stocks λ_i^* are obtained by running the above model. Then model 2 is run over a planning period of finite length assuming that $\lambda_i(T+1) = \lambda_i^*$. The accuracy of the approximation of the values of left over fish stocks with a planning period of a given length by the fish values at the steady state may depend on the length of this planning period. If the planning period is sufficiently long so that the system reaches or is close to the steady state, then it can be expected that the

approximation is reasonably accurate. However, such an assignment of terminal values should be by all means better than the zero terminal values in the model simulations.

Results and discussions

Long planning period with zero terminal values

The assumption that fish left over at the end of the planning period have no value (for example, Kennedy (1999) and Kennedy, Davies and Cox (1999)) can lead to higher optimal exploitation rates, particularly in the early years if the planning period chosen is not sufficiently long enough. Thus the choice of the length of the planning period can affect the optimal management policy, especially for long lived species such as the southern bluefin tuna. In order to investigate the impact of the length of the planning period on the optimal exploitation of the SBT fishery, model 1 was run over varying lengths (20, 40, 60, 80 and 100 years) of planning period. The optimal time paths of the total harvest, spawning stock biomass (SSB) and average value of fish[1] obtained with these model runs are presented in figure 1.

The optimal time paths obtained from the model runs suggest that the country groups should substantially reduce harvest in the first few years from the current level of around 15 000 tonnes a year to allow for rebuilding of stocks so that much higher harvests can be taken in later years. The average value of fish declined over time in all model runs as total harvest increased and also due to the assumption that fish stock left over has zero value.

The optimal time paths of total harvest, spawning stock biomass and average value of fish obtained when the planning period was 20 years differed significantly from the

[1] For each year, *t*, the average value of fish (*AVF(t)* in $/kg) is calculated by averaging the current value of fish across all age classes.

$$AVF(t) = \frac{1}{21}\sum_{i=1}^{21} \frac{\lambda_i(t)}{w_i} \cdot 1000 .$$

optimal time paths obtained for the first 20 years when the planning period was 40 years or longer. The optimal time paths for the first 20 years remained nearly the same between model runs with the planning periods of 40 years or longer. Therefore, a planning period of 20 years is too short to make the influence of the assumption that fish left over at the end of the planning period have zero value negligible and the optimal time paths are significantly changed when longer planning periods are used.

For a sufficiently long planning period, an assumption that fish have no value at the end of that period, may have no effect on harvests early in the planning period. However, the use of a planning period long enough to make the influence of this assumption negligible may cause computational problems in practical applications. In addition, most existing algorithms for optimisation are not capable of solving systems of large dimension. Shortening the planning period to circumvent such problems conflicts with the assumption that fish left over at the end of the planning horizon have no value. Thus any optimal solutions found for a short planning period with zero values for leftover fish stocks may not be optimal for long lived species such as the southern bluefin tuna.

Short planning period with positive terminal values

Positive values for left over fish stocks are assigned and model 2 is run over a 20-year planning period. The objective function in model 2 represents the sum of discounted net returns and consumer surplus over the planning period plus the sum over all ages of the discounted values of left over fish stocks in year 21. The solution to model 2 is obtained by maximising this objective function. As described earlier, three alternative methods are tested in specifying positive terminal values for fish stocks. The optimal time paths of total harvest, spawning stock biomass and average value of fish obtained from all three methods are presented in figure 2. The optimal time paths obtained by running model 1 over 20 and 100 year planning periods with the zero terminal value assumption are reproduced in figure 2 for the purpose of comparison.

Method–I

The optimal time paths obtained for the first 20 years when model 1 was run over 100 years with zero terminal values remained little changed, when the fish values at the 21st

year from this model run were specified as the terminal value in model 2. This demonstrates that the optimal solution for a problem with a short planning period with appropriately specified positive terminal values can well approximate the optimal solution for a problem with a long planning period and zero terminal values. As mentioned earlier, however, method–I is not of much practical use as that the model needs to be run over a sufficiently long period to produce appropriate terminal values.

Method–II

In this method, the values of fish stocks at the 20th year obtained from running model 1 (assumes zero terminal value) over 20 year planning period are used as the initial values in a series of iterative runs of model 2 (assumes positive terminal values) in order to find the best terminal value to be specified. The optimal time paths obtained by this method are very close to those obtained by method–I as well as the results of 100 year run of model 1 with zero terminal values. Unlike method–I, this method can be used in most practical situations given the problems involved in running the model over a sufficiently long planning period.

Method–III

In this method, the steady state terminal values of left over fish stocks obtained separately are specified in model 2. The optimal time paths obtained by this method failed to approximate the optimal time paths obtained for the first 20 years of the model run with a 100 year planning period with zero terminal values. This could be explained by that a planning period of 20 years is a too short a period for a long lived species like SBT to reach steady state and consequently the values of fish stocks at the end of that planning period may not be approximated by the steady state values.

However, this method should provide the best estimate of the terminal values of fish, if the planning period chosen is long enough for the model to reach the steady state. Model 1 of the SBT fishery specified in this paper failed to reach steady state even with a 150-year planning period. The optimal time paths obtained by running model 2 with 60 year planning period and the steady state terminal values are presented in figure 3. These optimal time paths were found to be closer to those of 100-year model run with

zero terminal values than the optimal time paths obtained when planning period was 20 years.

Conclusions

It was demonstrated with a bioeconomic model of the SBT fishery that different lengths of the planning period could result in different optimal time paths of harvest and spawning stock biomass if the fish stocks leftover were assumed to have zero values. This assumption can lead to higher optimal exploitation rates, particularly in the early years if the planning period chosen is not sufficiently long enough. Thus the choice of the length of the planning period can affect the optimal management policy, especially for long lived species such as the southern bluefin tuna. With the assumption of zero terminal values, the model may have to be run for a sufficiently long planning period to achieve a stable optimal solution.

It was also demonstrated that the optimal solution obtained with a short planning period with positive terminal values for fish stocks could well approximate the optimal solution that could be obtained with a long planning period assuming zero terminal values for fish stocks. The use of positive terminal values for fish stocks could be useful in cases where the solution for a long planning period cannot be achieved due to the limitations of optimisation algorithms as well as computation problems.

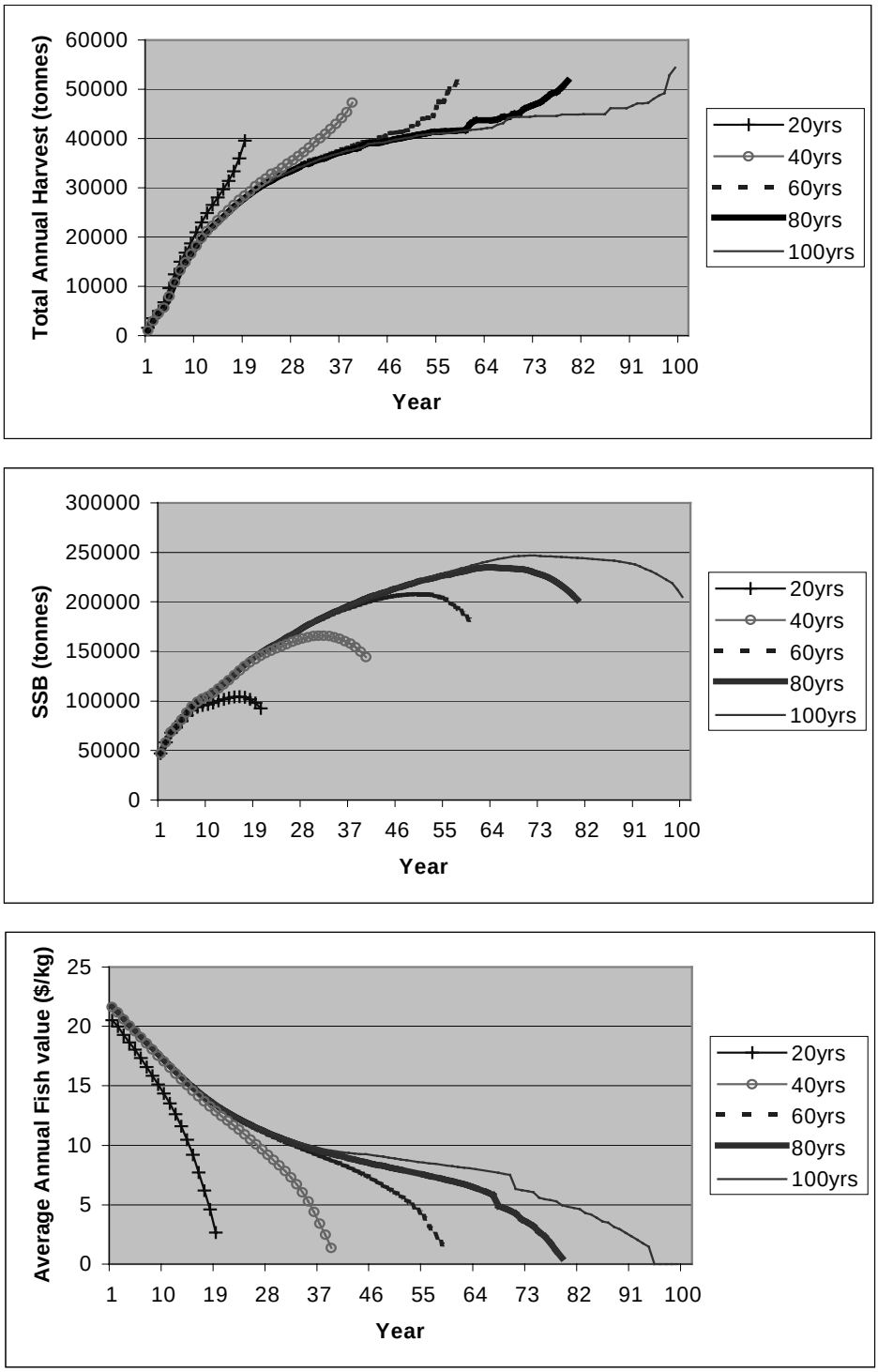

Figure 1. Optimal profiles of total harvest, spawning stock biomass and average fish value for different lengths of the planning period, where the fish left over are assumed to have no value.

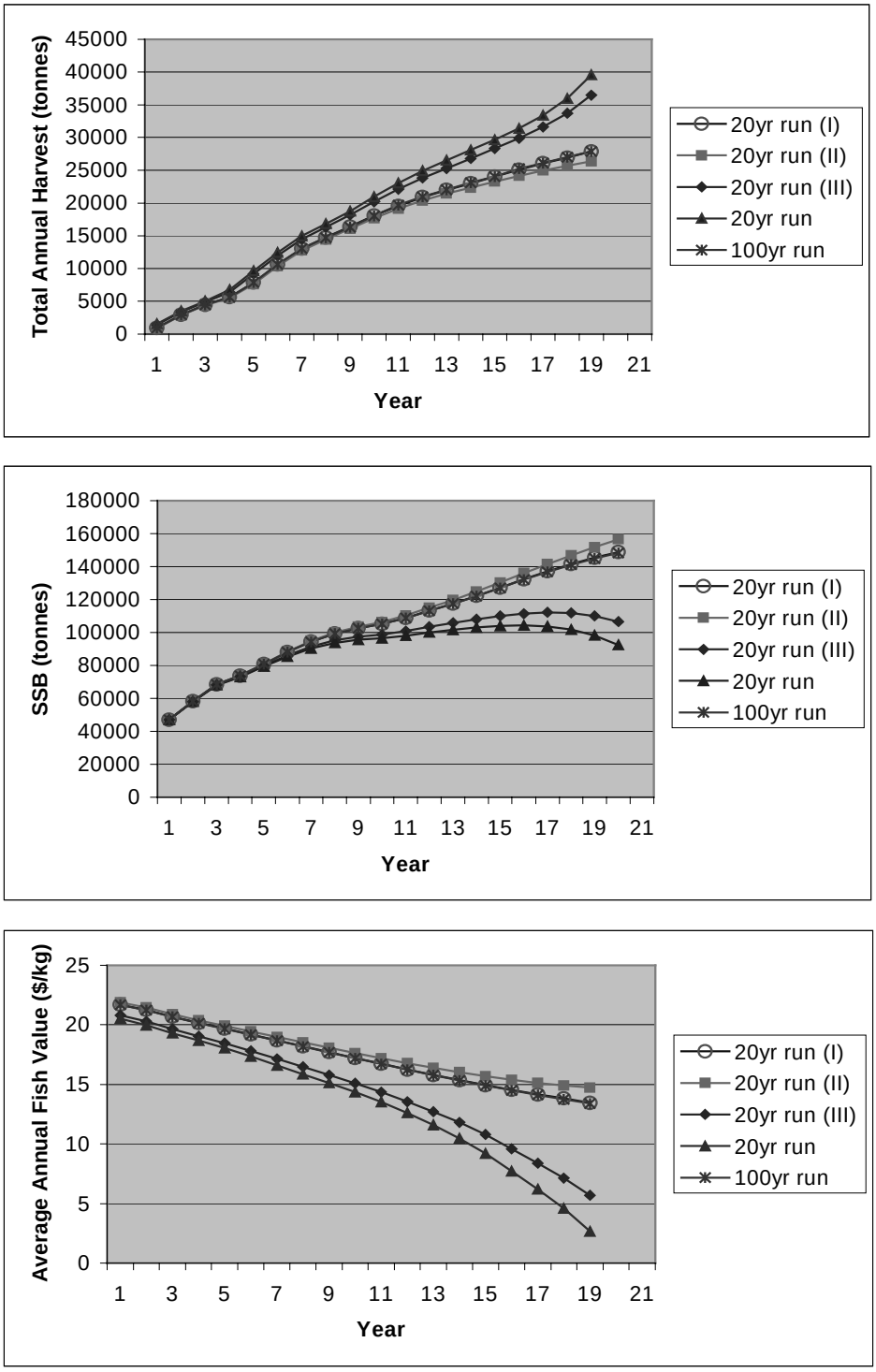

Figure 2. Comparison of optimal profiles of total harvest, spawning stock biomass and average fish value for a planning period of 20 years with three different settings of non-zero terminal values. The results are also compared with those for planning periods of 20 years and 100 years with zero terminal values.

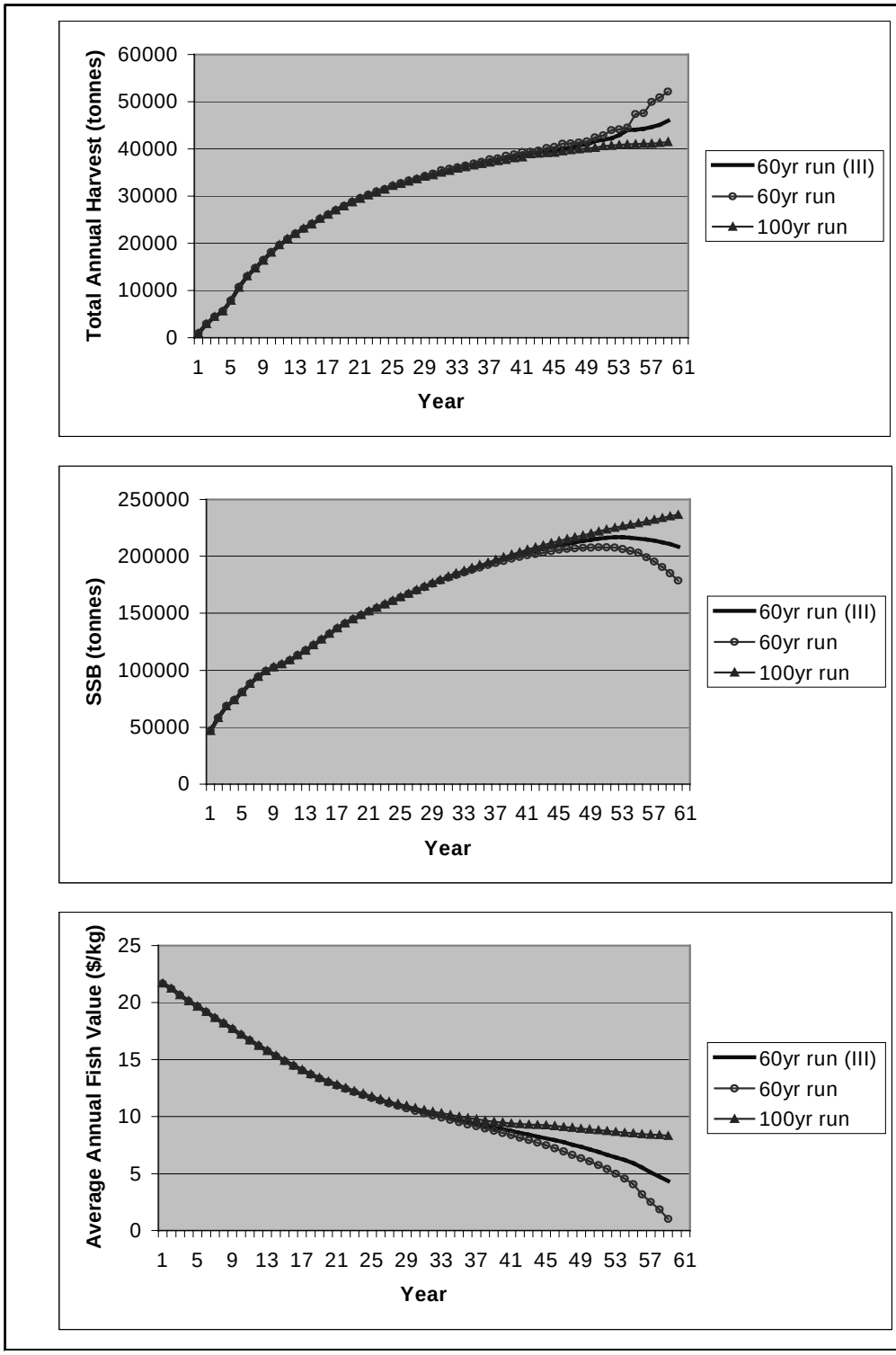

Figure 3. Optimal profiles of total harvest, spawning stock biomass and average fish value for a planning period of 60 years with the setting of non-zero terminal values by method–III, in comparison with the results for planning periods of 60 years and 100 years with zero terminal values.

Appendix A: Notation in the model

Indexes

t	Year (t=1,2,…,T)
i	Age (i=1,2,…,21) in years. 21 age classes are considered in the model
n	Country group (n=1 for Japan; 2 for Australia and New Zealand (ANZ) and 3 for Republic of Korea, Indonesia and Chinese Taipei (KIT))

Variables

$x_i(t)$	Number of populations of age class *i* at the beginning of year *t*
$s(t)$	Spawning stock biomass (in tonnes) in year *t*
$f_n(t)$	Fishing effort in year *t*
$g_i(t)$	Total mortality rate for age class *i* in year *t*
$h_{in}(t)$	Number of fish of age class *i* harvested by country group *n* in year *t*
$h_n(t)$	Weight of fish harvested from the ocean by country group *n* in year *t*
$o_n(t)$	Weight of fish harvested after fattening on farm by country group *n* in year *t*
$p_n(t)$	Price of fish (A$/kg) from country group *n* on Japanese market in year *t*
$TC_n(t)$	Total cost of harvest by country group *n* in year *t*
$TR_n(t)$	Total revenue of harvest by country group *n* in year *t*
$CS(t)$	Consumer surplus of Japanese consumers of SBT in year *t*
$NR_n(t)$	Net return from fishing by country group *n* in year *t*
$\lambda_i(t)$	Value of fish at age *i* in year *t*

Parameters

m_i	Annual natural mortality of fish at age *i*
q_{in}	Selectivity coefficient for fish of age *i* for fishing effort by country group *n*
α , β	Parameters for stock-recruitment function
w_i	Average catch weight per fish of age class *i* (kg)
sw_i	Average spawning weight per fish of age class *i* (kg)
pm_i	Proportion of fish of age *i* that is sexually mature
σ	Proportional weight increase after farming in Australia and New Zealand
η_{nn}, η_{nm}	Own and cross price elasticity of demand
r	Annual discount rate
A	Intercept vector $\mathbf{A} = (a_n)$ of the inverse demand equation

$\mathbf{B}$	Slope coefficient matrix $\mathbf{B} = (b_{nm})$ of the inverse demand
θ_n	Proportion of total cost to the total revenue in the base year
ρ	Proportion of fishing cost to the total cost for Australia and New Zealand
c_n	Cost (A$) per unit of effort for the country group *n*
c_f	Cost (A$) per unit of weight increase by farming

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