An agent–based bioeconomic model of a fishery with input controls

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Abstract: An agent–based bioeconomic fishery model was developed to assist in the design and evaluation of management instruments in an input controlled fishery. The agent–based structure of the model enables the choice of management instruments to be tailored specifically to account for the competitive 'race to fish' behavior observed in input controlled fisheries. The optimal season length and capital investment in the absence of market failure is determined by assuming there is only one agent in the fishery that can internalize all future benefits resulting from sustainable harvest levels. This is then compared with a number of agent–based scenarios, with varying restrictions on fishing inputs, where each individual agent seeks to maximize its own fishing returns subject to its expectations of the behavior of other agents. While the results are for a hypothetical fishery, the model provides estimates of the economic cost of this market failure, which in turn provides a benchmark against which the cost of management can be compared.

Keywords: *Agent–based modeling, Fishery management, Input controls, Effort creep*

1. INTRODUCTION

In order to overcome the problems associated with open access, fisheries management agencies have been established to control over–exploitation and over–capacity (Kaufmann et al. 1999). Whether through input or output controls, regulations are made to limit the harvesting of fishery resources to a volume that is considered sustainable over the long term and which maximizes economic returns.

In recent years computer modeling techniques have been developed to assist fishery managers design appropriate regulations. Fishery models range from biophysical models of fish stocks used to generate stock assessments and estimate the maximum sustainable yield, to integrated bioeconomic models that can comprehensively investigate economic efficiency concerns within fisheries. Because each of the agents, ie. firms or individuals, participating in a fishery seek to maximize its own interests, including agent–based behavior in bioeconomic modeling enables a more realistic assessment of management controls within a fishery.

2. THE MODEL FRAMEWORK

The model represents a single species fishery, based on tiger prawn data collected from the northern prawn fishery. It is a dynamic model containing both a biological and economic representation of the fishery and is formulated as an optimal control problem. With the model, the optimal length of the fishing season and annual investment in fishing power of vessels can be determined. The optimality criterion is that the net present value (NPV) of returns to the fishery over a given planning horizon is maximized.

2.1. Biological component

The stock–recruitment relationship defined by equations 1 and 2 determine the number of recruits to the fishery each year based on the size of the existing stock base (refer to appendix for variable and parameter definitions).

$$r(y+1) = \gamma_1 s(y) e^{\gamma_2 s(y)} \left(1+\theta(y)\right) \qquad (1)$$

$$s(y) = \sum_{w,a} x(y,w,a) \varsigma(w,a) \qquad (2)$$

There is an age structure to the stocks, with recruits entering the fishery at 6 months, and living for approximately 12 months. The model is based on a weekly time step and at each step the age of each cohort is progressed. Equation 3 calculates the number of fish stocks in the first age cohort, and equation 4 calculates the number of fish stocks for all other age cohorts. A slightly modified equation is used when estimating stocks in the final age cohort.

$$x(y,w,1) = r(y)\rho(w) \qquad (3)$$

$$x(y,w+1,a+1) = x(y,w,a) e^{-m-\sum_n f(y,w,n)} \qquad (4)$$

2.2. Behavioral Component

Fishing activity

The fishing activity relates fishing effort to catch (equations 5–12). Agents are able to increase fishing power, which in turn influences the effectiveness of fishing effort, by increased investment in vessel capital κ. The catch per unit of effort for each agent is monitored and fishing ceases for the year when the returns to fishing effort fall below a critical value.

$$\xi(y,n) = 1 + \alpha_0\left(1 - e^{-\alpha_1 \kappa(y,n)}\right) \tag{5}$$

$$q(y,n) = q_0(n)\xi(y,n) \tag{6}$$

$$E(n) = \pi_{mb}(n)\pi_{fdw}(n) \tag{7}$$

$$CPUE(y,w,n) = q(y,n)\sum_a x(y,w,a)\cdot g(a) \tag{8}$$

$$\eta(y,w,n) = \begin{cases} 1 & CPUE(y,w,n) \geq CPUEco(y,n) \\ 0 & Otherwise \end{cases} \tag{9}$$

$$f(y,w,n) = \eta(y,w,n)q(y,n)E(n) \tag{10}$$

$$E_{annual}(y,n) = \sum_w \eta(y,w,n)E(n) \tag{11}$$

$$C_{total,weight}(y,w,a) = \Big[x(y,w,a)(1 - e^{-m-\sum_n f(y,w,n)}) \sum_n f(y,w,n)/(m + \sum_n f(y,w,n))\Big]g(a) \tag{12}$$

Catch is derived from fishing mortality f and the level of stock in the fishery at any given point in time. The age structure of the prawn stocks makes it possible to calculate the weight of the catch at each time step. This in turn enables the prawn catch to be graded and priced accordingly for calculations of gross revenue.

Economic dynamics

Gross revenue from fishing is calculated using total catch, its composition by grade, and prices for the various grades of prawns (equation 13). Annual gross revenue (*AREV*) is calculated by aggregating the weekly gross revenue (*WREV*) over the year.

$$WREV(y,w,n) = \sum_j C_{weight,grade}(y,w,j,n)p(j) \tag{13}$$

Variable fishing costs incorporate packaging, fuel and crew costs based on ABARE surveys of the fishery. Packaging costs are dependent on the weight of the catch. Fuel costs are estimated as a function of effort and reflect both the price of fuel in the region and the geographic spread of fishing effort. Crew costs are estimated as a fixed percentage of catch revenue. The cost of capital locked up in vessels and the cost of any additional investments made to increase fishing power are represented by fixed annual costs. Net returns are calculated as the difference between gross revenue and total fishing costs (equations 14–16). They are reported in net present value terms.

$$VC(y,n) = \tau_p(n)\sum_{w,j} C_{weight,grade}(y,w,j,n) + \tau_f(n)E_{annual}(y,n) + \tau_c(n)AREV(y,n) \tag{14}$$

$$FC(y,n) = \pi_{cp}(n)\pi_{mb}(n)\kappa(y,n) \tag{15}$$

$$NR(y,n) = AREV(y,n) - VC(y,n) - FC(y,n) \tag{16}$$

2.3. Optimal control framework

The model is formulated as an optimal control problem to determine the optimal length of the fishing season and the annual cost of additional vessel capital. The criterion is to generate the highest possible net present value in the fishery over a five year planning horizon. The length of the planning horizon was dictated in part by computational limits. However, the species of prawn studied are a relatively short–lived species and a five year planning horizon is more than three times their expected lifetime. A genetic algorithm (GA) search technique was employed to find solutions for several problems formulated.

2.4. Modeling agents

Six agents, representing the vessels operated by six individuals or firms, were incorporated into the model. Each operator is assumed to control half of the vessels in one of three broad categories in the fleet: small, medium and large vessels. The three vessel categories are based on engine capacity. The cost structure and estimated fishing power for each category was based on survey data. The vessels within each category are assumed to be identical with the same fishing power and cost structure.

To model the competing interests of the agents in the fishery, the model contains independent GAs, in which each agent maximizes its annual net economic returns. The performance of an agent's strategy depends on the strategies employed by the other agents in the fishery. Robust strategies for each agent are developed and the model converges to a solution.

3. MANAGEMENT OF A SINGLE–FIRM FISHERY

A problem was formulated to investigate profit maximizing behavior in the fishery where one firm is able to fully capture the stream of returns generated over time. Unlike for the problem with multiple independent agents, a single GA was used to determine the joint optimal strategy of all six vessel groups. This generates a solution analogous to that for one firm owning all interests in the fishery. This solution provides the best combination of fishing inputs over the length of the planning horizon and the economically efficient harvest rate that is sustainable over the longer term.

With a relatively short planning horizon and if no economic value is placed on the fish stocks that remain at the end of the time horizon, even a single–firm fishery will decide to run down the fishery resource toward the end of the period. With computing capabilities limiting the length of the planning horizon, it was necessary to add a value for the stocks remaining at the end of the planning horizon to the objective function.

The objective function for the single–firm problem was therefore specified as:

$$Obj = \max \sum_{y,n} NR(y,n)(1+d)^{1-y} + \lambda s(y_T)(1+d)^{1-y_T}$$

w.r.t. $\kappa(y,n)$ and $CPUEco(y,n)$ (17)

where λ is the shadow price of s (see (2)) and y_T is the last year of the time horizon.

Although there are various procedures to obtain terminal values based on shadow prices (see Cao et al. 2001), a judicious guess of a shadow price for remaining stocks was found to eliminate the tendency of the model to run down the fishery resource towards the end of the period analyzed. The results presented below are based on a terminal value of \$8/kg. This value was selected because stock levels remaining at the end of the planning horizon, together with effort, catch and net returns, were found to be relatively stable for terminal values between \$6 and \$9 per kilogram.

3.1. Optimal fishing behavior

With the objective function (17) the optimal strategy of the single–firm controlling all six vessel groups generates an average annual catch of around 3800 tonnes and net economic returns of around \$100 million over the five years. Throughout the time horizon considered remaining stock levels are around 5000 tonnes.

The optimal combination of fishing vessels in this problem involves the two groups of large vessels fishing for most of the year with additional investment in vessel capital occurring in the majority of the five years of the planning horizon. Only one medium size vessel group is used, and for only a short period in the third and fourth years. It was not optimal for the remaining vessel groups to fish.

The tendency for the single operator to use larger vessels instead of smaller vessels reflects the greater efficiency of the larger vessels in the fleet. This is consistent with the past and likely future evolution of the fleet towards larger boats.

4. MANAGEMENT OF A FISHERY WITH MULTIPLE AGENTS

Agents in an unmanaged fishery have an incentive to over–fish and it is possible to model this behavior explicitly. A scenario was designed where each of the six operators, represented by six separate GAs, maximizes its annual net economic returns in each of the five years considered. Unlike the single firm scenario the agents place no terminal value on the stocks remaining at the end of the planning horizon. The objective function of this unregulated agent–based problem is therefore specified for each agent as:

$$Obj = max\ NR(y,n)(1+d)^{1-y}$$

w.r.t.: $\kappa(y,n)$ and $CPUEco(y,n)$ (18)

While this problem does not fully reflect an open access fishery because the number of agents in the model is fixed. However, capital is allowed to vary and the results reported below suggest that six agents are sufficient to capture the competitive behavior expected in a fishery without regulations.

4.1. An unmanaged fishery with multiple agents

A problem was formulated of an unmanaged fishery with six agents. Each agent was allowed to fish any weeks of the year and with as much investment in vessel capital as desired at the prevailing lease cost. The results show that agents adopt a strategy that involves significant fishing effort. All agents begin the five year period with significant investment in vessel capital and choose to fish a significant proportion of the year.

In the first year fishing is more than eight times as high as in the single–firm problem. Catch levels are more than three times as high and NPV returns almost double. This seriously depletes stock levels, with around 70 per cent less stock remaining at the end of the first year in this problem relative to the single–firm problem. In subsequent years fishing effort declines because lower stock levels result in significantly reduced catch and a decline in the returns to fishing effort. Over the five year planning horizon the net economic returns to the fishery are around 60 per cent lower than in the single–firm problem.

5. THE EFFECTIVENESS OF DIFFERENT MANAGEMENT CONTROLS

Without a guaranteed share of the total allowable catch at the beginning of the season, input controlled fisheries are characterized by 'race to fish' behavior. The inability to regulate all fishing inputs enables operators to substitute unregulated fishing inputs for regulated ones, thereby partially offsetting the targeted reduction in fishing effort. This effort creep problem requires continual monitoring and adjustment of regulations to ensure stock levels are not depleted over the longer term.

By imposing regulations on only the length of the fishing season it is possible to estimate the magnitude of effort creep resulting from vessel improvements. The model can also be used to analyse the effectiveness of a variety of different reductions in the length of the fishing season.

5.1. Restricting the length of the season

Initially the model was run with a fishing season lasting the entire year and this was then reduced in 10–week decrements to a 12 week fishing season. Reductions in the season length were found to have a positive effect on the net economic returns to the fishery. A 37 week long fishing season resulted in a NPV of economic returns of around $46.3 million over the five year planning horizon. Further reductions in season length generated higher net economic returns. With a season length of 22 weeks, the net economic return to the fishery over the planning horizon in net present value terms was an estimated $58.6 million, representing a more than 40 per cent increase from its value for the agent–based problem with an unrestricted fishing season.

While a shorter fishing season reduced fishing effort, improved the economic performance of the fishery and resulted in higher stock levels at the end of the planning horizon, figure 1 shows that the relationship between the length of the fishing season and final stock levels is not linear. Final stock levels appear to be relatively insensitive to a reduction in the fishing season from 32 to 22 weeks. In contrast, reductions from 42 to 32 weeks and from 22 to 12 weeks appear to have a more significant effect on stock levels at the end of the planning horizon.

This nonlinearity is likely to reflect the lumpy nature of investment in fishing capital. When the fishing season restrictions are not binding and some operators are choosing to fish fewer weeks, reductions in the length of the season have only a minimal effect on stock levels. In contrast, when operators are fishing the maximum possible number of weeks, reductions in the fishing season have a significant effect as reflected in the steeper sections of the curve in figure 1. However, reductions in season length may also trigger investment in vessel capital to compensate for the shorter season, resulting in a reduction in the magnitude of the impact on surviving stock levels.

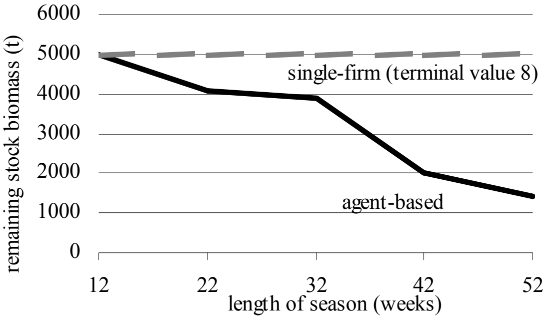

Figure 1. Variability in remaining stock biomass.

Table 1 reports the performance of the fishery under a number of different season length assumptions. The variability in the effectiveness of season closure in reducing effort and increasing stock levels is apparent when comparing the five week reduction from 37 to 32 weeks with a five week reduction from 22 to 17 weeks. Reducing the season from 37 to 32 weeks reduces fishing effort by more than 13 per cent and increases the NPV of the economic returns by more than 20 per cent. In contrast, reducing the season from 22 to 17 weeks is less effective. Effort is only reduced by around 7 per cent and the returns to the fishery are increased by less than 5 per cent.

In both cases overall catch levels are reduced by less than one per cent as operators increase their investment in vessel capital to compensate for the loss in season length. Figure 1 shows that if this effort creep is not restricted a season length of around 12 weeks is required to generate equilibrium stock levels considered sustainable in the single–firm scenario.

5.2. Reducing effort creep through restrictions on investment in vessel capital

When the fishing season was restricted to 22 weeks operators were observed to increase their investment in vessel capital, partially offsetting the attempt to limit fishing effort and preserve

Table 1. Effect of reduced season length on the performance of the fishery

	Year 1	Year 2	Year 3	Year 4	Year 5	Total
37 week season						
Effort (days)	23835	17563	15939	15260	14210	86807
Catch (t)	5395	4700	3409	3158	2826	19488
Stocks (t)	4774	3323	3196	2934	2874	
Net returns ($m)	21.2	11.6	5.4	4.5	3.6	46.3
32 week season						
Effort (days)	19215	15575	13790	13566	12824	74970
Catch (t)	4486	4716	3550	3458	3221	19430
Stocks (t)	5428	4159	4100	3937	3893	
Net returns ($m)	19.9	13.5	8.2	7.4	6.5	55.6
22 week season						
Effort (days)	15820	13895	13944	13496	11774	68929
Catch (t)	4105	4667	3767	3630	3228	19397
Stocks (t)	5652	4475	4375	4128	4060	
Net returns ($m)	19.7	14.5	9.4	8.2	6.9	58.6
17 week season						
Effort (days)	13923	12992	12523	12054	12504	63996
Catch (t)	3929	4619	3736	3609	3477	19371
Stocks (t)	5711	4620	4557	4364	4295	
Net returns ($m)	19.7	14.9	10.0	9.1	7.8	61.5
22 week season with no investment in vessel capital						
Effort (days)	16289	15134	14588	14665	14588	75264
Catch (t)	3565	4234	3679	3794	3732	19003
Stocks (t)	5739	4968	5145	5063	5069	
Net returns ($m)	18.1	14.3	11.0	11.0	10.1	64.4

stock levels. An additional problem, with a 22 week season and restrictions on investment in vessel capital was solved to analyse the magnitude of effort creep due to capital improvements and its effect on the performance of the fishery.

With no investment in vessel capital allowed to occur operators were found to increase the number of vessels that fished the entire 22 week season. The two operators running smaller vessels were found to fish every week of the season. The agents operating the larger vessels in the fleet also increased the number of weeks fished. Fishing effort, measured in days, increased by around 9 per cent. Despite this, constraints on investment in vessel capital to improve fishing power resulted in lower overall catch levels.

The net economic returns to the fishery when investment in vessel capital is constrained to zero were higher than for the problem with investment in capital increase fishing power. This problem provides an indication of the economic cost of this form of effort creep. Over five years in present value terms the net returns to the fishery are about $6 million higher. This represents the economic gain resulting from the elimination of inefficient investment in vessel capital. It also provides an indication of the upper limit that fishery managers could spend to eliminate the problem through the introduction of additional regulations.

In addition to increasing net economic returns to the fishery by around $6 million over the planning horizon, restricting investment in vessel capital leads to higher stock levels. When no restrictions are placed on investment in vessel capital it was estimated that the season length needed to be reduced to around 12 weeks to ensure stock levels similar to those for the single–firm problem to be sustainable over the longer term. When restrictions are placed on investment in vessel capital a 22 week fishing season generates final stock levels slightly higher than those for the single–firm problem. These results suggest that by controlling effort creep caused by investment in vessel capital it is possible to have a longer fishing season generating higher net economic returns while still ensuring the long term sustainability of the fishery resource.

6. CONCLUSIONS

Modeling competing agents in a fishery explicitly captures the ‘race to fish’ behavior observed in input controlled fisheries. Using this modeling approach it is possible to capture the incentive operators face to substitute unregulated fishing inputs as the use of regulated inputs are restricted. This insight into how operators are likely to react to different management controls in their efforts to maximize their economic returns can be used to better design fishery regulations. It also highlights the limited effectiveness of input controls to ensure sustainable harvest rates when too few fishing inputs are regulated. Estimates of the economic cost of effort creep can also assist fishery managers in making decisions to address the problem with maximum total economic efficiency. That is, to ensure the cost of management does not exceed the benefits of control.

Further work with this modeling approach could enhance the usefulness of the technique. Improved modeling, particularly the use of different solution techniques to reduce the computation burden, could increase the detail with which a fishery can be modeled. Additional development may also enable the analysis of the behavior of multiple agents within output controlled fisheries to compare the effectiveness of different approaches to fishery management.

7. REFERENCES

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8. APPENDIX: DEFINITIONS OF MODEL PARAMETERS AND VARIABLES

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a	age cohorts (52 weekly cohorts of adults of age 6 to 18 months)
w	week of the year (1–52)
y	year (1–5)
n	number of firms (1–6)
j	grade of prawns (1–5)

Parameters

γ_1,γ_2	parameters of stock–recruitment relationship
$\zeta(w,a)$	proportion of spawners at age a in week w
$\rho(w)$	proportion of recruitments in week w of year y
m	weekly natural mortality
α_0,α_1	parameters for estimate of fishing power
$q_0(n)$	default catchability of firm n (without new investment on vessels)
$\pi_{mb}(n)$	number of boats of firm n
$\pi_{fdw}(n)$	number of fishing days in a week
$\pi_{cp}(n)$	capital proportion of firm n for estimate of the fixed costs
$E(n)$	fishing effort of firm n in a week if fishing
$g(a)$	weight of fish at age a
$W(a,j)$	=1 if age a is in grade j, otherwise=0
$p(j)$	price of fish of grade j
$\tau_p(n)$	proportion of package costs of firm n
$\tau_f(n)$	proportion of fuel costs of firm n
$\tau_c(n)$	proportion of crew wage costs of firm n
d	annual discount rate

Variables

$s(y)$	spawning biomass of year y
$r(y)$	recruitments of year y
$\theta(y)$	stochastic shock on the recruitments of year y
$x(y,w,a)$	number of fish at age a in week w of year y
$f(y,w,n)$	fishing mortality by firm n in week w of year y
$\xi(y,n)$	fishing power of firm n in year y
$\kappa(y,n)$	leasing cost of firm n on vessels in year y (decision variable)
$q(y,n)$	actual catchability for firm n in year y
$\eta(y,w,n)$	fishing (=1) or not (=0) of firm n in week w of year y
$CPUEco(y,n)$	CPUE cutoff of firm n in year y (decision variable)
$E_{annual}(y,n)$	annual fishing effort of firm n in year y
$C_{total}(y,w,a)$	total catch of age a in week w of year y
$C(y,w,a,n)$	catch of age a in week w of year y of firm n
$C_{total,weight}(y,w,j,n)$	total catch in weight of age a in week w of year y
$C_{weight}(y,w,a,n)$	catch in weight of age a in week w of year y of firm n
$CPUE(y,w,n)$	catch per unit effort in week w of year y of firm n
$C_{weight,grade}(y,w,j,n)$	catch of grade j in week w of year y of firm n
$WREV(y,w,n)$	weekly revenue in week w of year y of firm n
$AREV(y,n)$	annual revenue in year y of firm n
$VC(y,n)$	annual variable costs in year y of firm n
$FC(y,n)$	annual fixed costs in year y of firm n
$NR(y,n)$	annual net return (current value) in year y of firm n