BOLETÍN

INSTITUTO DEL MAR DEL PERÚ

ISSN 0458-7766

Volumen 25, Números 1 y 2

Enero - Diciembre 2010

Callao, Perú

Tradeoff analysis for anchoveta management in Peru

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Introduction

Peruvian anchoveta fishery is the world's most productive fishery. Yet anchoveta comprise the food base for an immense ecosystem, so there is a clear tradeoff between fisheries profit (from extraction) and the productivity of higher trophic levels which rely on anchoveta for prey. We develop and implement a method to make this tradeoff explicit. Specifically, we develop a bioeconomic model, based on stock assessment data from Peru that helps managers explore alternative management options under different environmental scenarios.

The main features of this model are:

- Dynamic Model, with the ability to simulate and/or optimize over time
- Two spawning seasons per year, possibly with different recruitment success at different times of year
- Growth of individual anchoveta
- Stochastic environmental fluctuations that can affect (1) recruitment, (2) mortality, and (3) growth

Modeling overview

There are four distinct components of the bioeconomic model: a biological model, an economic model, a management function and an objective function. The purpose and current status of each component are summarized here, with details on each given in separate sections below.

The biological model represents anchoveta population dynamics and is intended to follow the assumptions made by the IMARPE stock assessment team as closely as possible. Current parameter values are based on data provided by Jorge Tam, Ricardo Oliveros and Erich Diaz. It is important to note that some of the data necessary for parameterizing the model (for example the stock recruitment data) were still being developed during the week of the international panel, and the parameters will need to be revised in collaboration with IMARPE scientists.

The economic model consists of functions necessary to translate harvest into profits by calculating how the price of anchoveta and the costs of fishing depend on the amount of fish being harvested. The price function has been parameterized based on historical price and landings data and the cost function is based on historical profit margins reported by companies harvesting anchoveta. These historical relationships will need to be revised because of changes in prices and costs resulting from the new individual quota system, and we hope to update these functions in collaboration with IMARPE and Peruvian economists.

The management function determines the total allowable catch and thus the fishing effort allowed in each time period. This fishing effort can be a function of the current biomass, the age structure, and the current environmental conditions. We have implemented three commonly used management functions, which provide useful reference points for comparison with more sophisticated strategies. The goal of PESCA is to implement the management function currently used by IMARPE and compare it to these reference functions as well as to candidate functions being considered by IMARPE for future management.

The objective function calculates the value of the fishery depending on the goals of management. We currently implement a function which combines the average long term biomass and the average long term profit. Depending on the parameters used, this function can represent a goal of maximizing profit, a goal of maximizing biomass or any combination of those two objectives. We could also incorporate other factors (e.g. temporal consistency of harvest or biomass) depending on the goals of IMARPE's management strategy.

Biological model

Let the population of adult anchoveta (aged 12 months and older) at the start of each six-month time step t be given by N_t. The biomass of these adults is B_t, whereas the biomass of juveniles (fish aged 6-12 months) is J_t. During each 6-month period, some

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November 23, 2009.

fraction F_t of the biomass is harvested so that the total biomass harvested in period t is given by:

$$H_t = F_t(J_t + B_t); \tag{1}$$

Juvenile fish become adults, and a fraction m of both juveniles and adults are lost to natural mortality, so that the new total number of adults is given by:

$$N_{t+1} = (1 - F_t)(1 - m)(N_t + J_t / w_r); \tag{2}$$

Where w_r is the average weight of a juvenile anchoveta, so that J_t/w_r is the number of juvenile anchoveta at the start of period t. The natural mortality rate m can also be structured to vary as a function of the environment. Fish are assumed to grow according to the Ford growth model, which matches the observed size at age data very closely and allows us to calculate adult biomass at time $t + 1$ as a function of the total biomass and numbers surviving the period:

$$B_{t+1} = \alpha(1 - F_t)(1 - m)(N_t + J_t / w_r) + \rho(1 - F_t)(1 - m)(B_t + J_t); \tag{3}$$

Where the α and ρ are the parameters of the Ford growth model. As with natural mortality rates, these parameters can be fixed, or can vary as a function of environmental conditions. Note that as long as mortality rates (fishing and natural) do not vary across age classes, this method of lumping adult fish and tracking only adult numbers and biomass will yield identical results to a model tracking each age class separately. We follow IMARPE's assumption that anchoveta stock and recruitment are related by a Ricker function, and Jorge Csirke's modification of the Ricker in which the relationship varies based on a concentration index Q which is related to oceanography. This means that the biomass of juveniles at the beginning of period $t + 1$ is a function of the spawning stock at the beginning of the previous period and the environmental conditions in that period:

$$J_{t+1} = w_r P_1 B_t \exp(-P_2 B_t Q_t); \tag{4}$$

Where P_1 and P_2 are the parameters of the Ricker function, and Q_t is a variable representing environmental conditions, which can be randomly drawn each time step or can be a random function of environmental conditions in previous time steps. Q values should be centered on 1, and low values represent good conditions, while high values are the opposite.

Economic Model

We assume price per tonne is a linearly declining function of the number of tonnes harvested with an intercept C_1 and a slope $-C_2$. The costs of fishing are proportional to the total effort (and thus the fraction of fish caught). θ represents this cost per unit effort. Profit for period t, π_t, equals revenues less costs:

$$\pi_t = (C_1 - C_2 * H_t)H_t - \theta F_t; \tag{5}$$

5 Management Function

The management function gives the fraction of fish allowed to be harvested in a time step F_t as a function of the state of the system at the beginning of the time step. We implement three management functions:

- Constant effort

$$F_t = g_0; \tag{6}$$

- Constant total allowable catch

$$F_t = \frac{g_1}{J_t + B_t}; \tag{7}$$

- Constant escapement

$$F_t = 1 - \frac{g_2}{J_t + B_t}; \tag{8}$$

Where in each case g_i modifies the intensity of fishing and F is constrained to be between 0 and 1.

Objective function

We allow for a multi-criterion objective function that simultaneously accommodates profit (from harvest) and conservation (standing biomass) of the species in question. We adopt a discount rate of 0, suggesting that we seek to maximize the steady state value of the objective function. The value of the system under a given management strategy is:

$$V = (1 - \beta)E(\pi) + \beta E(B)\tilde{B} \tag{9}$$

Where $E(\pi)$ is the expected average profit, $E(B)$ is the expected average biomass, β is the relative importance of biomass as a management goal, and $\tilde{\boldsymbol{B}}$ is a constant used to put biomass and profit on similar scales. When $\beta = 0$, the value depends only on profit, when $\beta = 1$, the value depends only on biomass, and intermediate numbers value both factors.

MATLAB Implementation

The main simulation code takes as input the parameters of the fishing mortality policy function, and returns as output the value of the objective function. While all code has been given to IMARPE, we copy below this main simulation code.

```
function[B,Profit,F,N,J,M] = PESCA_sim(mgt)

% PESCA - Programa para Evaluacion Scenarios Captura de Anchoveta v1.1
% Chris Costello, Andrew Rassweiler and Steve Gaines 8/14/2009
%
% PESCA_sim: this file simulates the biology and economics, for the period
% of yeas T and across the number of replicate simulations implied by the
% size of the Q matrix

global model

PESCA_params;

J=Jstart*ones(size(Q,2));
N=Nstart*ones(size(Q,2));
B=Bstart*ones(size(Q,2));
season = season_start;

for t=1:T

  if model == 1 %constant fishing
    F(t,:) = min(1,max(0,mgt));
  elseif model == 2 % constant escapement
    F(t,:) = min(1, max(0,1-(mgt*10^6)./(J(t,:)+B(t,:))));
  elseif model == 3 % constant TAC
    F(t,:) = min(1,(max(0, (mgt*10^6)./(J(t,:)+B(t,:)))));
  elseif model == 4 % simple adaptive style
    F(t,:) = min(1,(max(0, mgt(1) + (mgt(2)/10^6)*J(t,:) + (mgt(3)*10^6)./(J(t,:)+B(t,:)))));
  end

  M(t,:) = z0 - z1*Q(t,:);

  H(t,:) = F(t,:).*(J(t,:)+B(t,:));
  Price(t,:) = c1 - c2*H(t,:);
  Profit(t,:) = (delta^t)*(Price(t,:).*H(t,:) - theta*F(t,:));

  if t<T,
  N(t+1,:) = (1-F(t,:)).*(1-M(t,:)).*(N(t,:) + J(t,:)/c3);
  B(t+1,:) = alpha_g*(1-F(t,:)).*(1-M(t,:)).*(N(t,:) + J(t,:)/c3) + rho*(1-F(t,:)).*
  (1-M(t,:)).*(B(t,:)+J(t,:));
  J(t+1,:) = c3*a0*(a1^season)*B(t,:).*exp(-a2*B(t,:).* exp(1-Q(t,:)));
  end
  if season==1, season=0; else, season=1;end
  end
```

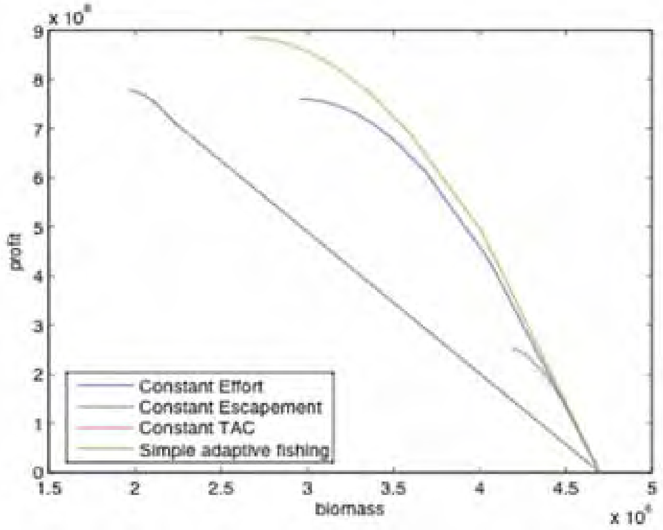

Figure 1.- Tradeoff between standing stock biomass (horizontal axis) and profit (vertical axis) for several different harvest policies.

Results

Because the model and parameterization are still in progress, these results are very preliminary. However, we believe they are illustrative of the kinds of results we would expect to obtain for the final version (for the follow-up meeting in March-April). The main results can be depicted on a single graph (Fig. 1). The graph illustrates the tradeoff between biomass and fisheries profit for a range of policy functions. There are four key insights from this graph:

Result 1. *Maximum profits are similar among (1) Constant Effort, (2) Constant Escapement, and (3) Adaptive fishing policies, provided that their parameters are optimized for the given objective. Maximum profit is somewhat smaller for a constant harvest policy, because with high environmental variability, the population crashes under a fixed harvest policy.*

Result 2. *Maximum biomass is the same under any fishing policy, because it entails no fishing at all (so the populations simply achieves carrying capacity).*

Result 3. *Substantial increases in biomass can be achieved at little or no cost to profit. This is achieved by switching from a policy that maximizes yields to a policy that explicitly considers biomass as part of the objective function. Importantly, it also entails switching to an adaptive policy.*

Result 4. *After rejecting constant harvest as a policy, the policies can be ordered (from worst to best): (1) Constant Escapement, (2) Constant Effort, (3) Adaptive. This ranking holds regardless of the weighting on biomass versus profit.*

Discussion

This short write-up contains a simple description of a bioeconomic model being developed between scientists and economists from the University of California and IMARPE. The model is in progress, and is still begin parameterized to closely match the stock assessment data generated by IMARPE. Despite its preliminary nature, several insights are possible. The most salient result thus far is that the form of the policy function (e.g. whether it targets a constant escapement, adapts to environmental conditions, etc.) plays an important role in the final outcome. Substantial gains in profit and/or biomass can be obtained, at little or no cost to the other objective, if this policy function is optimized. But to observe (and capitalize on) these gains requires simultaneously considering the profit of the fishery and the biomass left for higher trophic levels.

The model is currently focused on management strategies which respond to the current state of the population and environment. But the model is also potentially useful for evaluating management strategies which make use of climate forecasts such as those Francisco Chavez and the climate group has been working on. We can determine how management can best make use of these forecasts and can provide feedback to guide the climate prediction group. For example, we can evaluate the value of forecasts with different time horizons (e.g. 6 month vs. 12 month forecasts) to determine how far ahead it is necessary to predict.

Our intention is to continue to refine this model over the coming months, and to have a “final” version in IMARPE’s hands by the follow-up meeting (in 6 months). That will include a revised writeup and a MATLAB implementation of the bioeconomic tradeoff analysis tool. Our hope is that this tool is useful to IMARPE to explore the biological and economic consequences of alternative management strategies.