Stochastic bioeconomic modelling of alternative management measures for anchovy in the Mediterranean Sea

Christos D. Maravelias, Richard Hillary, John Haralabous, and Efthymia V. Tsitsika


The purse-seine fishery for anchovy in the Aegean Sea consists of two main fleet segments (12–24 and 24–40 m vessels); this paper investigates economically and biologically preferable effort and capacity scenarios for the fishery. Attention is paid to a bioeconomic analysis of fleets composed of segments with varying levels of efficiency (in terms of catch rate) and costs (fixed and variable) and the role this might play in optimal effort allocation at a fleet level. An age-structured stochastic bioeconomic operating model for Aegean anchovy (Engraulis encrasicolus) is constructed. It attempts to account robustly for the multiple uncertainties in the system, including (i) the effort–fishing mortality relationship, (ii) the selectivity, and (iii) the stock–recruit dynamics of the population. A method is proposed for determining the economically optimal level of long-term effort in a fishery such as this, with similar characteristics in terms of stock dynamics, fishery, and markets. Lower values of effort and capacity are predicted to yield greater future profit when viewing the fleet in its entirety, but even lower values may be advisable to maintain the long-term biological integrity of the stock. The results may prove useful in balancing the productivity of the stock with the harvesting capacity of the fleet, while managing to ensure the long-term profitability of the fleet along with the sustainability of the resource.

Keywords: anchovy, bioeconomic, capacity, effort, management, Mediterranean Sea, MSE, operating model, uncertainty.

Received 7 October 2009; accepted 13 February 2010; advance access publication 12 March 2010.

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Introduction

The fishery for anchovy (Engraulis encrasicolus) in the Aegean Sea is a major constituent of the Greek pelagic fishery in the area, which is itself a key fishery (Tsitsika et al., 2007) for the Greek fishing industry. The fishing fleet has a two-segment structure, with shorter vessels (denoted ps12, 12–24 m long) and longer vessels (denoted ps24, 24–40 m long). The shorter vessels are the largest both in terms of number (as of 2007) and in terms of the effort expended (days at sea as of 2007). The larger vessels report a higher cpue (catch per unit effort) than their shorter counterparts, suggesting that they are more efficient in terms purely of catching fish, but they also possess higher fixed and variable (per unit of effort) costs, suggestive of a potentially complex dynamic in terms of economically optimal levels of fishing effort for the fleet as a whole. Here, we develop an age-structured stochastic bioeconomic operating model (OM) for the anchovy stock and fishery to explore the potential effort and capacity scenarios for the fishery from the perspective of both economic and biological reference points. There are few examples of attempts to calculate economically optimal levels of effort using an age-structured bioeconomic OM such as that employed here, and a novel method is suggested and implemented. Earlier analyses (Maravelias and Tsitsika, 2008; Tsitsika et al., 2008) have suggested that the optimal capacity of the shorter vessels could be lower (in terms of the number of vessels), and here we explore different capacity measures in conjunction with various effort scenarios and economic reference points to choose between scenarios.

The assessment data for this stock and fishery are sparse (STECF, 2008). In this work, catch-at-age data from 2000 to 2007, acoustic survey data from 2003 to 2007 and spawning-stock biomass (SSB) estimates for 2003–2006 were used (GFCM, 2008; STECF, 2008). Key to the work in this paper is the inclusion of the uncertainty in key processes within the OM:

(i) Stock abundance: a residual bootstrap approach is used to explore the uncertainty in the tuned virtual population analysis (VPA) estimates of numbers and fishing mortality-at-age.

(ii) Stock–recruit relationship: life-history and meta-analytical techniques are used to estimate a plausible unfished SSB, residual variance, and autocorrelation estimated given this steepness distribution, and the bootstrapped assessment stock–recruit time-series.

(iii) Fishing mortality (F) is related to fishing effort by fleet segment to obtain a suitable sample of catchability parameters for the two vessel categories.

(iv) These are then combined (with fixed/variable cost data, fleet capacity, and age-structured price data) into a
stochastic-bioeconomic OM, complete with fleet disaggregated catch and profit functions.

The net present values (NPVs) of the future profits of the two fleet categories are used as the key economic reference points, in terms of both performance statistics and in identifying optimum levels of effort. Short-lived pelagic stocks, in particular anchovy, undergo occasional rapid collapses (Blaxter and Hunter, 1982). High rates of exploitation and environmentally driven (potentially successive) low recruitments combine with a short lifespan to reduce the spawning/exploitable biomass quickly to well below the viable levels. We also look at some precautionary limit/ target reference points for Aegean anchovy, and how the more bioeconomically driven effort strategies perform with respect to ensuring long-term biological viability.

The work was carried out under the EU project CAFÉ, which looked to derive relationships between fishing effort, capacity, and mortality and to use them to construct and evaluate related management strategies. In our work, we link tentative estimates with fishing effort, using capacity both to define relative boat efficiency and in the bioeconomic model, and explore the effort and capacity regimes that improve the biological and economic conditions for the population and fishery, respectively.

### The fleet and the fishery

The Mediterranean fisheries are extremely diverse, targeting a great number of species, and have an extensive range of fishing gears and methods. Catches are multispecies, and fishing is a major economic activity, in terms of jobs, revenue, and food supply. Purse-seining constitutes one of the most important fishing methods in the Mediterranean. Pelagic trawling is prohibited in the eastern Mediterranean EU fishery, so purse-seining is the main fishing method for small pelagic species, including anchovy. Each purse-seiner is responsible for searching for fish, and catching and transporting its own catches to the port. Fishing operations are exclusively by night (20:00–05:00), with each vessel having a crew of 5–10 persons. The fish are attracted to the upper water column by lamps that scatter light at the surface, and they are caught by the encircling net. All vessels conduct daily trips. The management of fishing effort alongside technical measures is the main tool used to preserve sustainable fisheries in the Mediterranean. Management regulations currently in force (EC, 2006) for the purse-seine fishery include mesh size regulations (>14 mm), technical measures such as closed seasons (December–February), closed areas, and fishing prohibition within specific distances from the coast (100 m).

Most Greek purse-seiners (97%; Hellenic Centre for Marine Research, HCMR, database) are divided into two fleet segments according to their length: 12–24 m (i.e. ps12) and 24–40 m (i.e. ps24). Such fleet segmentation follows the current national management protocol and is in agreement with the European Commission Data Collection Regulation Framework, which lays down specific rules and procedures for collecting fisheries data in EU Member States (EC, 2000, 2001). A time-series for the Aegean Sea purse-seine fishery (catches, effort, fixed and variable cost, income) is provided in Table 1, and specific technical characteristics of the fleet by segment, i.e. the number of vessels, vessel length, vessel tonnage, vessel engine power, in Table 2.

### Methods

The process of performing management simulations for the anchovy stock and fishery is, for convenience, split into two sections:

1. (i) establishing the \( F – \)effort–capacity relationship for the fleet exploiting Aegean anchovy, given the available stock assessment and fleet information;
2. (ii) defining and conditioning the bioeconomic OM used in the capacity- and effort-based management simulations.

### Table 1. Aegean purse-seine fishery effort, catches, cost, and income time-series by fleet segment.

<table>
<thead>
<tr>
<th>Year</th>
<th>Effort (vessel days)</th>
<th>Catch (t)</th>
<th>Cost (thousand €)</th>
<th>Income (thousand €)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>Anchovy</td>
<td>Fixed</td>
</tr>
<tr>
<td>ps12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>46 888.1</td>
<td>42 095.5</td>
<td>9 435</td>
<td>273.369</td>
</tr>
<tr>
<td>2001</td>
<td>43 410.7</td>
<td>41 484.4</td>
<td>7 604</td>
<td>277.552</td>
</tr>
<tr>
<td>2002</td>
<td>40 666.7</td>
<td>31 809.7</td>
<td>7 535</td>
<td>281.826</td>
</tr>
<tr>
<td>2003</td>
<td>40 790.6</td>
<td>33 543.6</td>
<td>12 550</td>
<td>279.070</td>
</tr>
<tr>
<td>2004</td>
<td>38 727.9</td>
<td>34 995.0</td>
<td>11 736</td>
<td>284.860</td>
</tr>
<tr>
<td>2005</td>
<td>40 577.2</td>
<td>36 064.4</td>
<td>10 823</td>
<td>297.747</td>
</tr>
<tr>
<td>2006</td>
<td>35 783.1</td>
<td>39 440.4</td>
<td>17 021</td>
<td>319.921</td>
</tr>
<tr>
<td>2007</td>
<td>30 348.1</td>
<td>28 866.0</td>
<td>14 315</td>
<td>308.399</td>
</tr>
<tr>
<td>ps24</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>1 958.2</td>
<td>1 808.5</td>
<td>615</td>
<td>16 572</td>
</tr>
<tr>
<td>2001</td>
<td>2 173.1</td>
<td>2 232.0</td>
<td>1 060</td>
<td>17 244</td>
</tr>
<tr>
<td>2002</td>
<td>2 553.4</td>
<td>2 218.3</td>
<td>1 113</td>
<td>16 533</td>
</tr>
<tr>
<td>2003</td>
<td>2 887.3</td>
<td>3 112.6</td>
<td>1 495</td>
<td>20 696</td>
</tr>
<tr>
<td>2004</td>
<td>3 889.1</td>
<td>6 671.1</td>
<td>3 878</td>
<td>33 789</td>
</tr>
<tr>
<td>2005</td>
<td>5 434.8</td>
<td>9 752.3</td>
<td>5 274</td>
<td>46 696</td>
</tr>
<tr>
<td>2006</td>
<td>5 486.4</td>
<td>9 814.4</td>
<td>6 462</td>
<td>54 526</td>
</tr>
<tr>
<td>2007</td>
<td>5 228.2</td>
<td>9 791.3</td>
<td>6 827</td>
<td>46 631</td>
</tr>
</tbody>
</table>
Defining and estimating the parameters of the \( F \)–effort–capacity relationship

A range of standard assessment models, such as extended survivors analysis (XSA; Darby and Flatman, 1994) and integrated catch-at-age analysis (ICA; Patterson and Melvin, 1995), has been translated into FLR [FLR: Fisheries Library in R—a suite of packages and procedures for stock assessments, management strategy evaluations (MSEs), including limited bioeconomic assessments, http://www.flr-project.org]. This means that the outputs from such assessments are in the same data structures as the OMs, so key information such as total mortality or trends in SSB/mean length (in the survey-based paradigm) are readily available for management simulations. The 2008 STECF Subgroup on the Mediterranean Sea (SGMED) reported that the anchovy assessment was preliminary and cautious, because it was based on a short time-series of data, not suitable to suggest reference points (e.g. \( B_{100} \)). Tuning data such as acoustic survey data-at-age and DEPM-derived estimates of SSB (EC, 2000, 2001) were used, along with catch- and weight-at-age and maturity data. Initial attempts using the ICA assessment algorithm (Patterson and Melvin, 1995) proved unsuccessful, primarily because of conflicting signals in the acoustic data, the catch data, and survey SSB estimates. Given these initial difficulties, the FLR version of the XSA algorithm (Darby and Flatman, 1994) was used to estimate population abundance and \( F \), using acoustic-survey data as the tuning index.

Catch, weight, and maturity data were available for the years 2000–2007 and ages 0–5, with the acoustic data covering the years 2003–2006 and ages 1–3 only. With such a sparse data array, it was considered appropriate to attempt to account for associated uncertainty in the historical stock dynamics, given that such information would form the basis of the simulation. This was achieved using a bootstrap procedure in the stock assessment (XSA in this case). The bootstrap method (Efron, 1979) is a simple yet efficient algorithm that, \( \text{inter alia} \), can be used to explore and estimate the uncertainty in parameter estimates. For our case, a residual bootstrapping method was used to generate a sample of abundance and \( F \) variables, as opposed to simply one best-estimate sample of population and fishery variables that are the basic product of most tuned VPA methods such as ICA or XSA. Considering a generic tuning index-at-age, \( I_{y,a} \), a set of residuals is obtained when the assessment model is fitted to these data:

\[
\varepsilon_{y,a}^j = g(I_{y,a}) - g(\hat{I}_{y,a}),
\]

where \( \hat{I}_{y,a} \) is the model-predicted index and \( g() \) is simply a function that relates the choice of error distribution (normal, \( g \) the identity; lognormal \( g = \ln() \), etc.). By resampling these residuals (with replacement) across years, but not across ages, given no guarantees of similar variance with age, "new" data may be generated as follows:

\[
\hat{I}_{y,a}^{new} = g^{-1}(B(\varepsilon_{y,a}^j) + g(\hat{I}_{y,a})).
\]

The function \( B() \) in Equation (2) represents the bootstrap with replacement algorithm, and clearly the algorithm is based on a simple rearrangement of Equation (1) combined with a residual bootstrapping procedure. The assessment model is then fitted to these “new” data and, by repeating the procedure a large number of times, one obtains bootstrapped quantities for all the assessment variables of interest.

The above procedure was performed 1000 times using the acoustic index-at-age for Aegean anchovy and for the chosen XSA assessment algorithm. Given the nature of tuned VPA methods, the estimates increase in precision as the year decreases with the most recent population and fishery variables being the most uncertain.

\( F \) is estimated using a non-separable VPA model in the XSA algorithm, meaning that one obtains the estimates of \( F \) for each year and for each age class. The intention is to establish a relationship between \( F \), effort, and capacity for the two fleets harvesting anchovy. To separate fishing pressure and selectivity/vulnerability, the following assumption is made:

\[
F_{y,a} = f_{y} f_{y,a}.
\]
where the selectivity (by year and age) is defined as follows:

\[ s_{y,a} = \frac{F_{y,a}}{\max_a(F_{y,a})}. \]  

which makes the assumption that there is always at least one age class that is fully selected in any given year.

Total catch and effort data are available for the two fleet segments. Effort is measured in fishing days, but it is important to account for the different efficiencies of the two segments—the larger boats have a higher cpue than the smaller boats, and this is where the notion of capacity and effort is included in the process. The cpue of each fleet segment is denoted \( X_{y,f} \) and a relative efficiency parameter \( \psi_{f_1,f_2} \) between two fleet segments \( f_1 \) and \( f_2 \) can be defined as follows:

\[ \psi_{f_1,f_2} = \frac{N_X}{\sum_{n=1}^{N_X} \frac{X_{y,f_1}}{X_{y,f_2}}}. \]  

The parameter \( \psi_{f_1,f_2} \) is a measure of the relative efficiency of fleet segment \( f_1 \) relative to \( f_2 \), using the harmonic mean (given that cpue is a rate) of the cpue ratio as the efficiency proxy, where \( N_X \) is the number of datapoints. Effort (for both fleet segments), \( E_{y,f} \), is related to total fishing pressure, \( f_y \), as follows:

\[ f_y = q(E_{y,12} + \psi_{24,12}E_{y,24}). \]  

In Equation (6), \( E \) is the effort, \( q \) represents the catchability of the 12–24 m fleet segment, and the relative efficiency (catch per day fished) of the 24–40 m fleet segment is used to rescale this catchability for the more efficient 24–40 m vessels. This leaves only the \( q \) parameter to be estimated to define the relationship between \( F \), effort, and capacity. The catchability parameter and the associated log-variance is estimated for each bootstrapped sample of \( f_y \). Figure 1 summarizes the estimates of \( q \) and the log-scale residual standard deviation (autocorrelation, time-series, and histogram), and Figure 2 is the resulting summary plot of the relationship defined in Equation (3).

The estimates of total fishing mortality are high (around 2 on average; Figure 2) and, given the extremely limited information available to assessment, it is difficult to verify these results. Absolute estimates of SSB are available for the stock and, although XSA cannot accommodate these estimates (and initial ICA explorations were unsuccessful), one can at least compare the XSA-derived estimates with the DEPM estimates of SSB. For the period 2003–2006, the survey-derived SSB estimates were 40, 23, 21, and 49 thousand tonnes, respectively, and from the assessment the (median) SSB estimates were 23, 42, 28, and 34 thousand tonnes, respectively. There is some agreement between the estimates in 2005 and 2006, but not for 2003 and 2004. At a basic level, however, the magnitudes are not far apart, suggesting that the abundance estimates from the bootstrapped XSA procedure (and, hence, the estimates of \( F \)) may not be completely wrong. From Figure 2, it is also clear that, even with a short dataseries,

**Figure 1.** Summary plot for catchability estimates (left) and associated log-scale residual standard errors (right). Autocorrelation plots are displayed on the top (to diagnose potential issues within the bootstrapping procedure), time-series plots in the centre, and histograms at the bottom.
the fit of observed $F$ and effort data to the posited effort–capacity–fishing mortality relationship is reasonable.

**Defining and conditioning the bioeconomic OM**

Here, we deal with the conditioning (Rademeyer et al., 2008) of the Aegean anchovy bioeconomic OM. Above, we covered the means of generating bootstrapped assessment-derived estimates of $F$, then estimating a relationship between $F$, effort, and capacity proxies for each fleet segment. Here, the key elements of the biological and fishery simulation models need to be defined and estimated, e.g. stock–recruit dynamics and uncertainty, the harvest control rule (effort-based in this case), and bioeconomic indicators.

For any such age-structured population, one is required to define some relationship between spawners and recruitment that introduces new animals into the population. Given such a short dataset (8 years), it was deemed necessary to use as much existing knowledge of the reproductive capacity of anchovy as possible, given the obvious paucity of data. In terms of the intrinsic rate of increase, $r$, estimates for anchovy around the level of 0.6–0.8 (Froese and Pauly, 2007) have been reported. There is a relationship between key stock–recruit parameters (specifically the gradient of the relationship at zero spawner abundance) and other life-history characteristics (survival, maturity, growth).

This relationship is encapsulated in the Euler–Lotka equation (Fisher, 1930), where the intrinsic rate of increase, $r$, estimates for anchovy around the level of 0.6–0.8 (Froese and Pauly, 2007) have been reported. There is a relationship between key stock–recruit parameters (specifically the gradient of the relationship at zero spawner abundance) and other life-history characteristics (survival, maturity, growth).

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This relationship is encapsulated in the Euler–Lotka equation (Fisher, 1930), where the intrinsic rate of increase, $r$, the recruits-per-spawner biomass at zero spawners, $a$, the maturity, $m$, natural survival probability, $p_s$, and the weight, $w$, are related as follows:

$$ \sum_{n=0}^{\infty} e^{-n}m_\alpha w_\alpha \pi_\alpha = 1. $$

Crucially, this means that if we know $r$ and the other life-history parameters, we can estimate the maximum recruits-per-spawner, $a$, which in turn a key parameter in almost all stock–recruit relationships. In particular, there is a clear link between $a$ and the steepness of the Beverton–Holt parameterization of the stock–recruit curve:

$$ \alpha = \frac{4h}{\rho(1-h)} $$

where $\rho$ is the SSB per unit recruit. The parameter $r$ was assigned a mean of 0.7 and a CV of 0.2, so that the interquartile range covered the values 0.6–0.8. The Euler–Lotka equation was then solved for the steepness (via $a$) for each sample of $r$. Given these steepness values, the virgin biomass, $B_0$, the residual variance, and the autocorrelation were then estimated for each bootstrap sample of anchovy SSB and recruitment. Figure 3 summarizes the stock–recruitment parameters used for the biological OM, and with future selectivity defined using normalized historical fishing mortality-at-age and the stock–recruit parameters estimated, we are in a position to define the projection dynamics of the biological OM.

For ages ranging from 0 to $A$, assuming the last age to be a plus group and the numbers-at-age for ages 1 to $A-1$, the numbers-at-age follow the following dynamics:

$$ N_{y+1,A+1} = N_{y,A} \exp(-F_{y,A} - M_A), $$

For age $A$ (plus group), we have

$$ N_{y+1,A} = N_{y,A-1} \exp(-F_{y,A-1} - M_{A-1}) + N_{y,A} \exp(-F_{y,A} - M_A). $$

Recruits are stochastically related to the SSB at the end of the year as follows:

$$ N_{y,0} = \frac{\alpha SSB_{y-1}}{1 + \beta SSB_{y-1}} \exp(\gamma). $$
In Equation (11), \( e_y \) follows the following autoregressive moving average process:

\[
  e_y = \omega e_{y-1} + \xi_y, \quad (12)
\]

where

\[
  \xi_y \sim N(0, (1 - \omega^2)\sigma^2_x).
\]

The assumption in Equation (13) is that median, not mean, recruitment is the deterministic value of recruitment, given SSB and the stock--recruit parameters. Catches in numbers are defined via the Baranov catch equation:

\[
  C_y = \frac{F_y}{F_y + M_a} N_y (1 - \exp(-F_y - M_a)). \quad (14)
\]

The final part of the OM is to define the economic variables used in the simulations. Price data are available by age, and both fixed and variable cost information are available for the two fleet segments (Table 1). The gear-specific annual profit is defined as follows (\( g \) is also fleet):

\[
  \pi_{g,y} = \sum_{a=0}^{A} p_a C_{g,a} W_{g,a} - c_v E_{g,y} - c_d v_y. \quad (15)
\]

In Equation (15), \( p \) is the price, \( c^v \) the mean cost per unit effort per vessel, \( W \) the number of vessels of that gear type, \( E_{g,y} \) the effort per vessel (in d) for that gear type, and \( c_d \) the fixed costs per vessel. Assuming a discrete discount rate, \( \delta \), the future profits (over a timeline defined by \( T \)) discounted to the present, NPV is defined as follows:

\[
  \text{NPV}_g = \sum_{t=1}^{T} \pi_{g,t} (1 + \delta)^{-t}. \quad (16)
\]

It is both a useful performance metric to assess the economic performance of a candidate management strategy and a key variable from which one can derive optimal (or economically) effort regimes. To estimate the optimal levels of total effort (in fishing days and assuming a fixed effort split between the fleet segments), we maximized the expected NPV for the total, ps12, and ps24 fleet segments \([E(\text{NPV}^*)]\) over a 100-year projection period, chosen for the following reasons.

(i) It effectively ensures that one obtains equilibrium conditions (at \( \sim 38 \) generation length) and loses the historical effect (as far as possible) of the initial conditions; although with non-zero discount rates, this is never truly attainable in practice.

(ii) It is a way to maintain sustainability. For example, when calculating stochastic maximum sustainable yield (MSY), one would maximize the total expected equilibrium catch, not the NPV, over the 100-year period. If we chose only 10 years, for example, the economically optimal level of effort may well exceed MSY, and in some cases also \( E_{\text{crash}} \).

One can also optimize the total effort for both fleet segments, not just the total NPV, because this can be a useful tool for understanding in some sense the relative economic efficiency of the two fleet segments with respect to differences in the optimal effort levels. Changes in capacity will not influence the optimal levels of effort, because they only result in changes in the fixed cost portion of the NPV [Equation (15)], which is independent of effort. Given the socially important nature of the fishery and the wish to ensure sustainability, we assumed a 2% discount rate throughout the analyses.

Reference points

In terms of economic reference points, we have detailed how economically optimal levels of effort were calculated, but we also require more biologically focused reference points. Stocks such as anchovy can, when heavily exploited, undergo rapid population crashes (e.g. Bay of Biacy anchovy; Uriarte et al., 1996) when there are successive years of poor recruitment. With this in mind, we defined the precautionary SSB level to be half the virgin level \([B_{\text{ps}} = E(0.5 B_0)]\), and the limit SSB level to be 20% of virgin SSB \([B_{\text{lim}} = E(0.2 B_0)]\).

Results

Table 3 details the main economic results for the various effort and capacity scenarios considered. Three potential optimization options were permitted: where the expected NPV of the total fishery was maximized (for some fixed effort value with a fixed effort share between the two segments), or where it was optimized for each of the two fleet components. In terms of capacity-reduction scenarios and given the results of the detailed capacity study performed by Maravelias and Tsitsika (2008), there was (i) the no-reduction case, (ii) a 20% reduction in capacity of both the ps12 and the ps24 segments, and (iii) a 40% reduction in the ps12 segment and a 20% reduction in the ps24 segment. In terms of the prohibition on fishing juveniles, a simple reduction in selectivity of age-0 anchovy by 100% was assumed as an alternative to the (already low) model-estimated juvenile selectivity.

Figure 4 shows that when optimizing the total effort based on the expected NPV of the ps12 segment, a strong reduction in current effort is required (almost 30%), but when optimizing the NPV of the ps24 segment, an increase in effort is required (\( \sim 10.5\% \) increase). When calculating the effort that optimizes the total fleet NPV, predictably one finds the answer between the two single-segment values, though far closer to the ps12-estimated effort level (an effective reduction in effort of \( \sim 16\% \)). This is not because it is the dominant economic performer (in terms of gross revenue or discounted profits), but because it experiences a much stronger economic impact from higher effort levels than the ps24 fleet does from reduced effort levels (Figure 4) relative to current effort. Note that all economically optimal effort levels were significantly lower than the expected MSY levels. For such a stock and fishery with a short-lived species, with medium to high levels of steepness and where the selectivity curve lags behind the maturity curve, the expected effort that would achieve MSY would be almost 50% larger than the current effort. This is not to say that such an MSY value is any way sensible, but merely that as would be expected, the economically optimal levels of effort (given a longer-term perspective on sustainability and low discount rates) are lower than those expected to yield MSY.

In terms of the capacity reduction scenarios, given that the ps12 fleet, even with a 40% reduction in capacity, was still able to fish the number of days estimated as optimal (as was the ps24 fleet up to a capacity reduction of 20%), all capacity reduction scenarios increased the expected optimal NPV. If both segments can maintain the range of effort levels at a lower capacity, then from
Equation (15), a reduction in the number of vessels will automatically increase profits. The maximum capacity reduction scenarios yielded the highest expected NPVs (Table 3), but note that further reductions in capacity in either fleet segment would likely result in a limit on the amount of effort able to expended by the fleet, so impacting profitability and resulting in potentially lower levels of NPV. As for the prohibition in fishing juveniles, always this acted to increase the expected NPV (compared with the model-predicted juvenile selectivity), likely because of the low price of juvenile fish and the value attained by allowing them to grow into higher-priced fish and maintain the stock abundance at a slightly higher level.

Table 3. Effort optimization values for maximizing the total, ps12, and ps24 expected NPV under various capacity/F scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cap12 (% reduction)</th>
<th>Cap24 (% reduction)</th>
<th>F-at-age 0 (% reduction)</th>
<th>Optimize NPV</th>
<th>Total NPV (million €)</th>
<th>ps12 NPV (million €)</th>
<th>ps24 NPV (million €)</th>
</tr>
</thead>
<tbody>
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<td>E1</td>
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<td>66.365</td>
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Cap12, capacity of ps12 fleet segment; Cap24, capacity of ps24 fleet segment; F-at-age 0, fishing mortality on age-0 group.

Figure 4. Effort optimization curves for total, ps12, and ps24 NPV at various capacity/F scenarios.

Figure 5 is a graphical summary of the predicted response of future anchovy SSB under various effort scenarios and in relation to the precautionary and limit SSB reference points. Figure 5a shows future SSB under current (2007) effort conditions; the predicted distribution of SSB is contained largely between \( B_{pa} \) and \( B_{lim} \) (more specifically, the interquartile range is contained therein). The same is true for a 17% reduction in total effort (equating to an effective 1-month closure of the fishery), but the median SSB is consistently higher than under status quo effort conditions. For an effort reduction of 30% (equating roughly to the effort reduction required to maximize the ps12 NPV), the upper end of the interquartile range is
eventually coincident with $B_{pa}$ with the median higher than both the status quo and 17% effort-reduction scenarios. Only with a 50% reduction in total effort does the population eventually exceed the $B_{pa}$ level with a probability $>0.5$. In terms of economic performance over the 10-year projection period, Figure 6 shows the expected (discounted) future profits for each scenario. The initial effort reductions (when enacted) decrease the profitability of the fleet, but this is quickly ameliorated as the stock recovers in size (and age structure) and catch rates increase. Even for the 50% effort reduction, the profitability of the fleet eventually increases above the status quo effort scenario.

Discussion and conclusions

In the absence of TACs or quotas in the Mediterranean, the fisheries management system depends heavily on direct effort restrictions through the control of fleet capacity/fishing effort and technical measures, including limited entry. We used a stochastic age-structured bioeconomic OM developed in the FLR framework (Kell et al., 2007) to explore the economically optimal levels of effort and capacity within the Aegean anchovy fishery, and the impact of various scenarios on the stock from a biologically focused perspective. The work represents the first comprehensive investigation of bioeconomic management strategies for anchovy in the Mediterranean.
With various concerns and reservations raised in the latest Scientific, Technical and Economic Committee Study Group on the Mediterranean (STECF, 2008) and General Fisheries Commission for the Mediterranean (GFCM, 2008) about this stock assessment, it was preferred to use the XSA-tuned VPA algorithm in conjunction with a residual bootstrap procedure to estimate stock abundance and to account for the uncertainty therein. Given that the relevant data only allow the estimation of 8 years of population trends (2000–2007), life-history techniques are used with meta-analysis to obtain a distribution for the steepness of the anchovy stock–recruitment function, so permitting estimation of virgin spawn biomass and the construction of an anchovy stock–recruitment relationship. The anchovy fleet can conveniently be split into two segments, comprising shorter (ps12) and longer (ps24) boats, and a disaggregated effort–fishing mortality relationship was established that was able to cope with the different efficiencies (in terms of realized F per day fished) between the two fleet segments. With age-specific price data and detailed fixed and variable cost data, we were able to construct the bioeconomic component of the OM. To estimate the optimal levels of effort, a 100-year projection period (to try and ensure sustainability) was used over which the expected NPV (the sum of future profits discounted to the present) was computed.

Results suggested, assuming a fixed effort split between the fleet segments, that if the fisheries management system aimed to maximize the ps12 NPV by optimizing the total fleet effort, then a 28.95% reduction in total effort was required. Alternatively, if the aim was to maximize the ps24 NPV by optimizing the total fleet effort, then the findings show that a 10.53% increase in total vessel days would be necessary. Finally, if the criterion was to maximize the total NPV of the entire purse-seine fleet by optimizing the total fleet effort, then a 15.79% reduction in total effort would be required. All economically optimal effort values were well below the value expected to result in MSY. The catch and subsequently the discounted profits of the fishery would initially drop with the introduction of management measures enforcing effort limitations, but profits would eventually increase above those predicted at current effort levels, even within a 10-year projection. Obviously, the greater the effort reduction, the greater the catch reduction, and this short-term effect may act as an impediment to putting into force such measures. In the longer term, though, effort control would increase the levels of stock biomass, which would raise catch rates and economic efficiency, resulting in eventually greater profit. In practice, one might suggest a suitable effort-reduction path over the shorter 10-year time-frame that maximizes the short-term NPV, yet still attains optimal (long-term) effort levels.

In terms of the performance of the various capacity scenarios considered, given that even for a 40% reduction in the ps12 capacity level and a 20% reduction in the ps24 capacity level, the remaining fleet would be able to expend the same effort as of 2007, there was no impact on the optimal effort levels with respect to capacity. Given this, it was expected that reductions in the capacity of both fleet segments would result in higher future discounted profits, which was duly observed. The current model uses a simplified index of effort (days at sea) and an accordingly simplified variable cost structure, so the use of such a model to assess the optimal levels of capacity would seem to be unwise. Indeed, other econometric methods have been applied to the fishery (Maravelias and Tsitsika, 2008) to assess optimal capacity, and the results demonstrated that the ps12 segment was operating at ~60% capacity and the ps24 segment at ~79% capacity, providing the motivation for the capacity scenarios employed here. It was considered better to use the model applied here to test the implications of various capacity scenarios than to attempt to estimate them concurrently with optimal levels of effort. Moreover, if one was able somehow to limit the selection of juvenile (age 0) anchovy to effectively zero, an increase in future profitability for both fleet segments would be seen, given both the low price of anchovy and the associated increase in stock size and enhanced value of the fish. Overall from an economic perspective, it would appear that a global decrease in effort of around 15–17%, a decrease in the ps12 capacity of 40%, a decrease in the ps24 capacity of 20%, and a ban on catching juvenile fish would yield the greatest future discounted profits (over the 100-year time-frame and for a 2% discount rate).

To evaluate the biological implications of these more economically driven effort and capacity scenarios, we defined some basic precautionary reference points based around fractions of the unfinished SSB, i.e. $B_0$. The precautionary and limit reference points were set at $B_{pa} = E(0.5B_0)$ and $B_{lim} = E(0.2B_0)$, respectively. Although the level of $B_{lim}$ makes sense (it would be the level of SSB at which the steepness-dictated reduction in realized mean recruitment would begin to become apparent), the precautionary level of SSB would, at first sight, seem to be conservative. The reason for evaluating such a value was that similar anchovy stocks have undergone rapid crashes (e.g. Peruvian anchovy, Bay of Biscay anchovy) as high exploitation, accompanied by successive poor recruitments or other adverse conditions, decimated the spawning stock. Relative to these two reference points, the status quo and 17 and 30% less effort scenarios could not move the future (10-year) SSB interquartile range above $B_{pa}$, but they did succeed in moving it farther from $B_{lim}$ (Figure 5). Only a 50% reduction in total effort was able eventually to bring SSB
above $B_{pa}$ with a probability >0.5. The conclusions drawn from both STECF and GFCM study groups (GFCM, 2008; STECF, 2008) regarding the assessment of this anchovy stock were considered preliminary and cautionary, because they were based on a short time-series of data, not suitable for suggesting the reference points $B_{pa}$ or $B_{pun}$. This means that the key biological parameters that dictate productivity (virgin biomass, steepness, selectivity, etc.) are probably not well estimated at present. The work here using a bootstrapped XSA procedure was merely a first attempt to remedy this situation. Evidently, the biological reference points used do not form any kind of definitive performance statistic, but rather are illustrative and motivated by issues relating to problems seen in similar stocks. Although the results suggest that, from an economic perspective, a smaller fleet expending fishing effort would be preferable, and from a biological perspective, meaningful reductions in effort may serve to avoid unwanted dramatic population reductions, if one were to adhere to the principle of MSY, then a large and economically unwarranted increase in effort and/or capacity would be required. This is not to say that MSY has no place in the management of fish stocks, but that for populations such as this where the animals mature faster than they are selected and have reasonably good reproductive capacity, it can often result in answers that are difficult to credit.

We refrain from reaching any strong conclusions in terms of management of this specific fishery given the somewhat immature nature of the tuning data and stock assessment process. The work did not seek to include the effect of the stock assessment and data collection process in an MSE framework (fixed-effort management procedures require no stock assessment information), but it did attempt to evaluate the robustness of the effort and capacity scenarios to biological and economic system uncertainties. The approach demonstrated how one can parameterize a fully age-structured bioeconomic model even with limited biological data, account for uncertainty in a systematic manner, and how one might estimate optimal levels of effort in such a formulation. The use of multiple objective criteria (not just economic or purely biological ones) also allows one to compare and contrast the relative merits of even simple effort management strategies. There is an obvious social cost related to any type of effort and/or capacity reduction, and with multiple fleet segments, there are likely to be different goals in play. The idea of profit here really relates to the private benefit function of the two fleet segments. Perhaps, one way to look at the impact (and for potential information on optimal reduction paths for both effort and capacity) is to think about the social benefit related to the fishery as a whole, as opposed to the private benefit to the fishing fleets. Tax and other state-bound income are collected from fishing fleets, and there are other sources of value added too. Focusing on capacity reduction in terms of buybacks, the costs of such a scheme can perhaps be considered against the potential increase in the state income expected from a more profitable fishing fleet reduced in size. By looking at social benefit in terms of private fishery profits, buy-back costs, and fishery-related tax and general value added, perhaps one can assess the feasibility (via cost–benefit analysis) of a proposed capacity reduction, or even estimate a more general optimal capacity-reduction scheme.

**References**


doi:10.1093/icesjms/fsq018