Bioeconomic equilibrium and supply regime for a multi-species multi-fleet fishery: an analysis in the Mediterranean Sea

LUCA MULAZZANI*, GIULIO MALORGIO*

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Abstract

Fishery authorities are often led by poor scientific knowledge about fish stock dynamics and socio-economic concerns, to adopt management choices that are similar to an open access situation. Management of transboundary fish stocks is particularly problematic because national authorities can pursue different objectives. Supply regimes are also affected by biological variables, strategic interaction and management choices. In this paper, we present a bioeconomic model in the case of two fleets competing for two target species. A numerical application, using a surplus production model and game theory, is performed for the small pelagic fishery in the Adriatic Sea. Different policy choices are assumed in the framework of competitive games.

Keywords: *bioeconomic models, multi-species, non-cooperative games, shared stocks, supply regimes.*

Résumé

Les autorités responsables de la pêche ont souvent une connaissance insuffisante des dynamiques des stocks de poissons et des soucis socio-économiques, ce qui les amène à adopter des décisions en matière d'aménagement qui se rapprochent d'une condition d'accès ouvert. L'aménagement des stocks de poissons transfrontaliers s'avère être particulièrement critique étant donné que les autorités nationales peuvent poursuivre des objectifs différents. Les régimes d'approvisionnement sont aussi influencés par les variables biologiques, l'interaction stratégique et les décisions dans le domaine de l'aménagement. Dans cet article, nous allons illustrer un modèle bioéconomique concernant deux flottes qui sont en compétition pour deux espèces cibles. En nous appuyant sur un modèle de production excédentaire et la théorie des jeux, nous proposons une application numérique pour la pêche des petits pélagiques dans la mer Adriatique. Différentes options de politiques sont avancées dans le cadre des jeux compétitifs.

Mots-clés: modèles bioéconomiques, multi-spécifiques, jeux non-coopératifs, stocks partagés, régimes d'approvisionnement.

1. Introduction

In February 2012 the European Commission announced the 2020 Strategy where bioeconomy is seen as a key element for sustainable growth in Europe. Agriculture, forestry, fisheries and aquaculture, requiring several essential and limited resources to produce biomass, are all included under this framework. Fisheries, however, represent a special case, where a common, biologic, renewable resource is directly harvested for food uses. As all common-pool resources, fish stocks are characterized by high rivalrousness and difficult (but not impossible) exclusion; in other words, excluding potential appropriators or limiting appropriation rights of existing users is nontrivial and the yield of the resource system is subtractable (Ostrom *et al.*, 1994). Since Hardin definition, the term "tragedy of commons" has expressed the degradation of the environment to be expected whenever many individuals use scarce resource in common (Ostrom, 1990).

Prescriptive policies have considered extremely diverse solutions, including centralization (unitary decisions for a particular resource), privatization (through a set of well-defined property rights), and co-management. In the absence of well specified and transferable property rights, market failure occurs. On the other hand, it is also possible to talk of "State failure" when public presence increases, because politicians and managers have a few interests to resist to interest groups' pressures (i.e. fishermen), while optimal management should occur when the state adopts the same maximization objective of a private (Pearce and Turner, 1991). Other economists (Randall, 1981) acknowledge that imposed property rights are frequently in contrast with the ethical values of a society; in other words, optimal solutions cannot neglect the institutional setting of the community. On a similar ethical field, we find the discounting issue, considering that different communities can have different discounting behaviors, privates and states have different objectives, and discounting rates are generally decided by the current generation without taking into account the interests of the future generations.

As it is well known, many European fish stocks have been overfished for decades and many fishing fleets are too large for the available resources. As a consequence of overfishing and overcapacity, most of the EU's fishing fleets are either running losses or returning low profits. As attested by the Green Paper on the Reform of the EU Common Fisheries Policy (2009), *an important consequence* (and cause) *of the vicious circle of overfishing, overcapacity and low economic resilience is high political pressure to increase short-term fishing opportunities at the expense of the future sustainability of the industry.* Although the EU policy will be strongly based on the Maximum Sustainable Yield (MSY) principle, national authorities are not always able to control overcapacity because they are concerned about socio-economic problems (unemployment) and be-

* University of Bologna, Department of Agricultural and Food Sciences.

cause there is no consensus between the scientific community and the fishermen's organizations on the necessary corrective measures.

This paper proposes a theoretical bioeconomic framework that models the interaction between two fleets competing for two target species (mixed fisheries). The Schaefer model (1954) is used as the underlying biological framework for the application of game theory. Our main objective is to establish the effect of the two players' different policy choices on fishing capacity (and consequently on supply); the effects on the stocks, such as the potential extinction of one of the two species, will also be illustrated. Subsequently a numerical simulation will be performed using parameters that are available for the Adriatic small pelagic fishery: steady-state solutions will be shown for two non-cooperative games, and sensitivity analyses will illustrate changes in equilibrium determined by the variation of certain parameters. Change in prices will be used for the specific objective to show supply regimes in the case of competitive mixed fisheries.

2. Materials and methods

2.1. The theoretical framework

In the following paragraphs, we will describe the two-species, two-fleets, bioeconomic model. The biological component is based on a surplus production model, the Schaefer model (1954), while game theory is used to represent strategic interaction between fleets.

In the Schaefer model it is assumed that one fish stock, as a single unit, follows a logistic growth function. The parameters of the function are the intrinsic growth rate and the carrying capacity, which is the maximum biomass that can live in the sea basin. Catches are proportional to biomass and to fishing effort considering a catchability coefficient. Under these assumptions, Maximum Sustainable Yeald (MSY) can be obtained regulating the fishing effort in order to maintain stock biomass at the half of the carrying capacity.

Game theoretical applications analyzing fisheries began with the work of Munro (1979), who adopted a surplus production model to investigate how player asymmetry can impact solutions. The dynamic analysis by Munro preceded the static formulation by Mesterton-Gibbons (1993). For a review of the game-theoretic models of fishing, see the papers of Bailey *et al*. (2010) and Sumaila (1999).

In this paper, we will consider a game with two players, more precisely two national management authorities (they could be public authorities or producers' organizations). Each management authority has a large number of fishermen to represent and to control. Fleet characteristics and technology are homogeneous within each management authority but different between them; thus, we can consider them as two different fisheries, even if the two target species are the same. We suppose two possible management options for the management authorities, which respond to different economic, social, and political objectives (or pressures). The first option is open access: there are no limits to the entry of new firms and to the increase of fishing effort, and so a fishery's profit is completely dissipated (Gordon, 1954). The second option occurs when the authority decides to regulate the fishing effort to maximize the steady-state profits of the fishery managed. In neither case is there cooperation between the two management authorities.

We will not consider the discount rate in the profit maximization objective (such as in Ruseski, 1998; and in Wachsman, 2002). However, the bioeconomic literature teaches that the two management options can be also seen as the limit cases of the same problem: the maximization of steady-state profits corresponds to a zero discount rate solution, while open access corresponds to an infinite discount rate solution (Clark and Munro, 1975).

As anticipated, the model includes two target species. We will consider the steady-state situation for which population is constant (catches equal growth). Assuming logistic growth (Verhulst, 1838), the steady-state for both stocks is

$$B_a = \left(1 - \frac{q_{ai}E_i + q_{aj}E_j}{r_a}\right)K_a \tag{1}$$

$$B_p = \left(1 - \frac{q_{pi}E_i + q_{pj}E_j}{r_p}\right)K_p \tag{2}$$

where r_a, r_p, K_a, and K_p are the *intrinsic growth rates* and the *carrying capacities* for the two stocks *a* and *p*; E_i and E_j denote the fishing efforts of the two fisheries *i* and *j*; q_{ai}, q_{aj}, q_{pi}, and q_{pj} are the *catchability coefficients* of each fishery for each stock. It is clear that the stock biomass depends on all fishing efforts.

The profit of a fleet is given by the difference between income and the total costs. In the steady-state condition, assuming that catches are directly proportional to effort and stock biomass, the profit equations of the two fisheries are

$$\pi_i = p_{ai}q_{ai}K_a\left(1 - \frac{q_{ai}E_i + q_{aj}E_j}{r_a}\right)E_i + p_{pi}q_{pi}K_p\left(1 - \frac{q_{pi}E_i + q_{pj}E_j}{r_p}\right)E_i + m_iE_i - c_iE_i \tag{3}$$

$$\pi_j = p_{aj}q_{aj}K_a\left(1 - \frac{q_{ai}E_i + q_{aj}E_j}{r_a}\right)E_j + p_{pj}q_{pj}K_p\left(1 - \frac{q_{pi}E_i + q_{pj}E_j}{r_p}\right)E_j + m_jE_j - c_jE_j \tag{4}$$

where *p* is the price (different for species and for fishery), π and *c* denote the profits and unit costs of the two fisheries, and *m* is any supplementary revenue proportional to effort (e.g., subsidies or incidental catches of non-target species).

Each of the two fisheries can be managed with either the open access option or the profit maximization option. Four combinations are then possible: both players adopt the open access option, both adopt the profit maximization option, *i* adopts the open access option and *j* the profit maximization option, and viceversa.

With the open access option, the profit of equation (3) must result nil. So (supposing that player *i* adopts this option), the equilibrium fishing effort will be

$$E_i = \frac{-E_j\left(\frac{p_{ai}q_{ai}K_a q_{aj}}{r_a} + \frac{p_{pi}q_{pi}K_p q_{pj}}{r_p}\right) + p_{ai}q_{ai}K_a + p_{pi}q_{pi}K_p + m_i - c_i}{p_{ai}q_{ai}^2K_a + p_{pi}q_{pi}^2K_p} \quad (5)$$

On the other hand, if player *i* adopts the profit maximization option, the first order condition is . Thus, deriving (3) and solving by E_i, we obtain

$$E_i = \frac{-E_j\left(\frac{p_{ai}q_{ai}K_a q_{aj}}{r_a} + \frac{p_{pi}q_{pi}K_p q_{pj}}{r_p}\right) + p_{ai}q_{ai}K_a + p_{pi}q_{pi}K_p + m_i - c_i}{2\left(\frac{p_{ai}q_{ai}^2K_a}{r_a} + \frac{p_{pi}q_{pi}^2K_p}{r_p}\right)} \quad (6)$$

Equations (5) and (6) represent the reaction curves (Figure 1a) of player *i* with the two options, taking into account the fishing effort of player *j*. We will call these curves the *open access curve* and the *profit maximization curve*. It is not surprising that (assuming a logistic growth) the effort chosen by *i* with the profit maximization option is exactly the half the equilibrium effort obtained with the open access option. This result corresponds to the property of the Gordon-Schaefer model (Gordon, 1954; Schaefer, 1954), in which the fishing effort that corresponds to the Maximum Economic Yield (MEY) is exactly half the bioeconomic equilibrium effort of an open access fishery (Open Access Equilibrium, OAE).

However, these equations hold only if the combination of effort of the two fisheries does not cause the extinction of any species; on the contrary, if extinction occurred, the linearity of the reaction curves would not be continuous. Extinction occurs when the result of (1) and (2) is zero. Solving for E_j for both species, we obtain the following extinction curves:

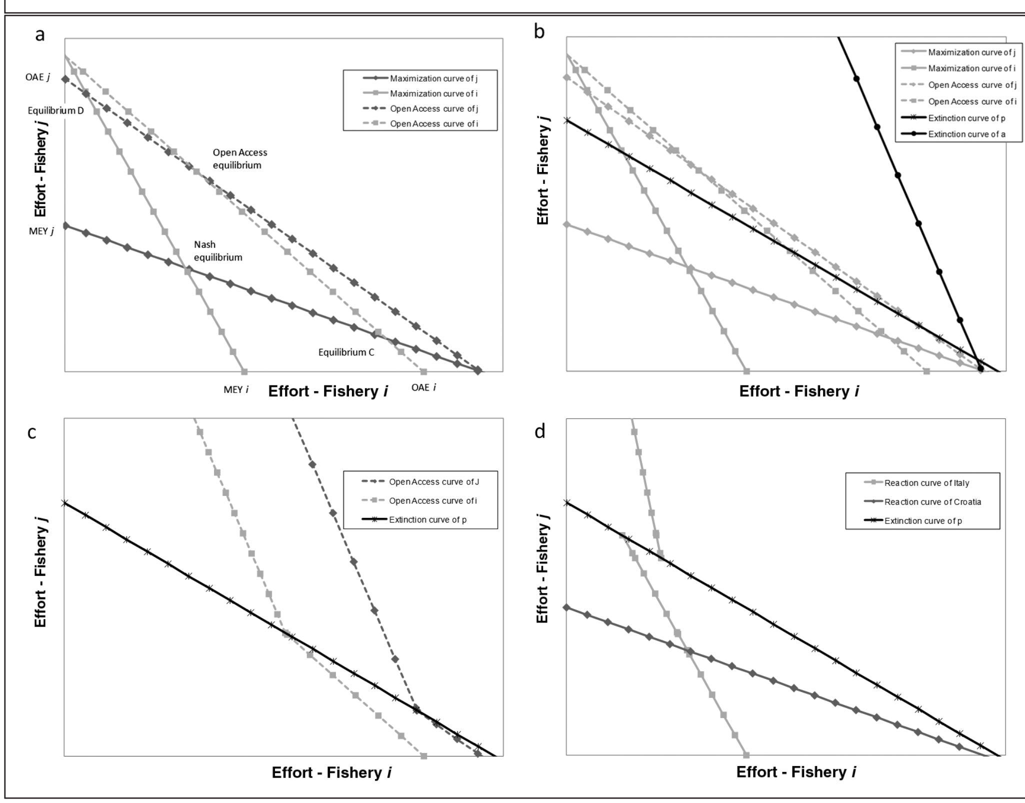
$$E_{ja} = \left(1 - \frac{q_{ai}E_i}{r_a}\right)\frac{r_a}{q_{aj}} \quad (7)$$

$$E_{jp} = \left(1 - \frac{q_{pi}E_i}{r_p}\right)\frac{r_p}{q_{pj}} \quad (8)$$

At the points where reaction curves intersect extinction curves, we find discontinuities[1] (Figure 1b,c,d). Beyond the extinction of one species, players' strategies change: (5) and (6) do not hold when one species has died out because we would obtain negative catches and revenues, which have no meaning. For effort levels beyond the extinction of one species, reaction curves must include only the parameters (*r*, *K*, *q*, and *p*) of the surviving species.

We can conclude that in this model, the steady-state fishing effort of the two fisheries is function of several biolo-

Figure 1 - *The theoretical framework for a two-player competitive game: reaction curves and equilibrium points in the case of open access and profit maximization and extinction curve (a); extinction curves are included in the frameworks (b); discontinuities in the reaction curves due to the extinction of one species: the open access case (c) and the profit maximization case (d).*



[1] The intersection of the extinction curve with the open access curve creates a removable discontinuity; it is noteworthy that with a single target species, the open access curves of the two fisheries are parallel lines, implying that the more efficient fishery causes the disappearance of the less efficient. On the other hand, the intersection of the extinction curve with the profit maximization curve creates a jump discontinuity.

gic parameters (r and K), technological and fish behavior parameters (q), economic parameters (p, m and c), and management choices. Together with steady-state effort, steady-state stock biomasses and catches can be established as well.

If we use a chart to illustrate the changes in (steady-state) quantities due to changes in prices, we obtain a classic supply curve. Supply regime in fisheries is not an extensive research area (Nielsen, 2006b): literature departs from Copes (1970) who introduced the idea of the backward-bending supply curve. More recently, Nøstbakken and Bjørndal (2003) estimated the supply curve for North Sea herring, while Nielsen (2006 a, b) focussed on East Baltic cod and on alternative supply regimes in the presence of regulated and restricted access. Our numerical example shows how changes in the price of one species, through long-run bioeconomic feedbacks, affect the supply of both species and the supply shares of both fleets.

2. Case study and data

The described model is used to determine steady-state solutions and to perform sensitivity analyses with a numerical example. The situation of different fleets competing for the same resources is very common worldwide, for example when industrial and artisanal fisheries coexist. Furthermore, these fleets may belong to different countries, and this is the case of shared stocks. On the other hand it is generally difficult to have reliable biological parameters for surplus models.

In this context, the small pelagic fishery in the Adriatic Sea is an interesting example of the management of transboundary fish stocks, the resources of which are shared by Italy and Croatia . The two species involved in this mixed fishery are sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*).

For this fishery, an attempt to estimate the parameters of the Schaefer model has been carried out by Mulazzani (2011) using non-linear minimization techniques with the CEDA software (Kirkwood *et al*., 2001). The same procedure has been followed in this paper after a minor change in the measurement of fishing effort time series (see Mulazzani 2011 for details).

The use of a surplus production model may seem inappropriate for small pelagic species. The literature on small pelagics warns that a deterministic relationship between stock biomass and its growth rate could be weak for these species because stock (specifically recruitment) fluctuations can be mainly due to environmental conditions (water temperature, salinity, nutrient concentration, etc.) and complex ecological cycles (Aguero and Gonzalez, 1996; Chavez *et al*., 2003; Murphy, 1967). Furthermore, for the Adriatic Sea, the use of Virtual Population Analysis (VPA) to assess small pelagic stock is well established (Cingolani *et al*., 1996; Santojanni *et al.,* 2001, 2003, 2005, 2006, 2009). These studies confirm that stock-recruitment relationships are not well defined. Given these assumptions, an age-structured model or a different type of model in which recruitment is explicitly considered may seem more appropriate. Nevertheless, for the Adriatic small pelagics, stock-assessment results obtained with a non-equilibrium version of the surplus production models differ little from VPA results (Mulazzani, 2011).

The main benefit of such a model is that it can be easily integrated into economic equations to determine steady-state solutions. Furthermore, the surplus production model explicitly takes into account fishing effort, whose regulation is the key tool in the management of the Mediterranean fisheries. Finally, we have to highlight that this paper does not attempt to provide a definitive answer for the future (and the best management options) of Italian and Croatian small pelagic fisheries, but it does illustrate a schematic approach that provides a qualitative understanding of the systems, showing possible changes in the equilibrium as a response to changes in exogenous variables or in management policies.

While information on the Italian fishery is highly documented, few data were available for the Croatian fishery until now; thus, many assumptions are required to construct a numeric example of the Adriatic bioeconomic system. The only study known to attempt to quantify the Croatian small pelagic fleet was performed by the AdriaMed[3] project in 2004.

Table 1 shows the estimated Schaefer parameters (following the procedure used in Mulazzani 2011). The MSY for anchovies is close to present catch levels (approximately 40,000 metric tons), while the MSY for sardines would be higher (approximately 60,000 metric tons) than present catches owing to stock overexploitation. Fishing effort is measured as total engine power multiplied by the year fraction when fishery is allowed (normally 11 months).

Official Italian statistics from IREPA and independent studies (Silvestri and Maynou, 2009) allow researchers to know the total costs of the small pelagic fishery. Unit cost[4] of fishing effort is calculated as the 2005-2008 average.

No data are available on Croatian costs. Different assumptions can be made concerning this issue. In the end, we decided to decrease the Croatian variable and crew costs (compared to Italy) using as benchmarks the energy costs and personnel costs published by Eurostat for Italy and Croatia (Eurostat online database). Using this approach, the Croatian variable costs (essentially fuel) are assumed to be 29% lower than the Italian costs, while crew costs are assumed to be 67% lower. Finally, the total and unit costs of fishing effort are calculated.

Prices are considered exogenous in this paper. Average Italian prices (for the period 2005–2008) of sardine and an-

[2] The Slovenian fishery is ignored in this paper, considering that catches are less than 1% of total Adriatic catches.

[3] AdriaMed (Scientific Cooperation to Support Responsible Fisheries in the Adriatic Sea) is an FAO Regional Project.

[4] In the long-term perspective of steady state, all costs are considered as variable costs.

Table 1 - *Parameters used in the model.*

Biological and technical variables			
Variable	**Method of estimation**	**Anchovies**	**Sardines**
Carrying capacity (*K*)	CEDA procedure	181039 tons	2364204 tons
Intrinsic growth rate (*r*)	CEDA procedure	0.99967	0.10568
Catchability coefficient of Italian fishery (q_i)	CEDA procedure	1.25E-05	1.27E-06
Catchability coefficient of Croatian fishery (q_j)	Calculated assuming Croatian effort 1.6 higher than Italian effort	2.21E-06	2.48E-06
Technical and economic variables			
Variable	**Method of estimation**	**Italy**	**Croatia**
Anchovy's price (c_a)	Italy: average price using official data (IREPA) Croatia: calculated using prices in Chioggia market as benchmark	1.31 €/kg	2.64 €/kg
Sardine's price (c_p)	Italy: average price using official data (IREPA) Croatia: calculated using prices in Chioggia market as benchmark	1.25 €/kg	1.73 €/kg
Cost per unit of fishing effort (*c*)	Italy: calculated using official data (IREPA) and literature Croatia: calculated using energy costs and personnel costs (Eurostat) as benchmarks	1126.8 €	798.2 €
Extra revenue (bycatch) per unit of effort (*m*)	Italy: calculated using official data (IREPA) Croatia: assumed equal to Italy	117.5 €	117.5 €

chovy are taken using IREPA statistics. Again, local information on Croatian prices is missing. Data exist only in international markets: for example, Croatian small pelagics are normally sold in the Italian market of Chioggia; furthermore, we can consider the unit values of both Croatian and Italian exports to Slovenia. Using these figures as benchmarks (average 2005-2008), we can conclude that price of Croatian sardines is approximately 1.4 times higher than the Italian price, while the price of Croatian anchovies is approximately double that of Italian anchovies[5].

Finally, IREPA data are used to estimate the average (period 2005–2008) revenue of the Italian fleet due to catches of non-target species (bycatch). Bycatch revenue per unit of fishing effort is calculated and assumed equal for Croatia.

3. Results

3.1. Steady-state solutions

Italian and Croatian parameters will be used to solve the theoretical game for two players and two species. In table 1, we describe the parameters used to calculate the steady-state solutions.

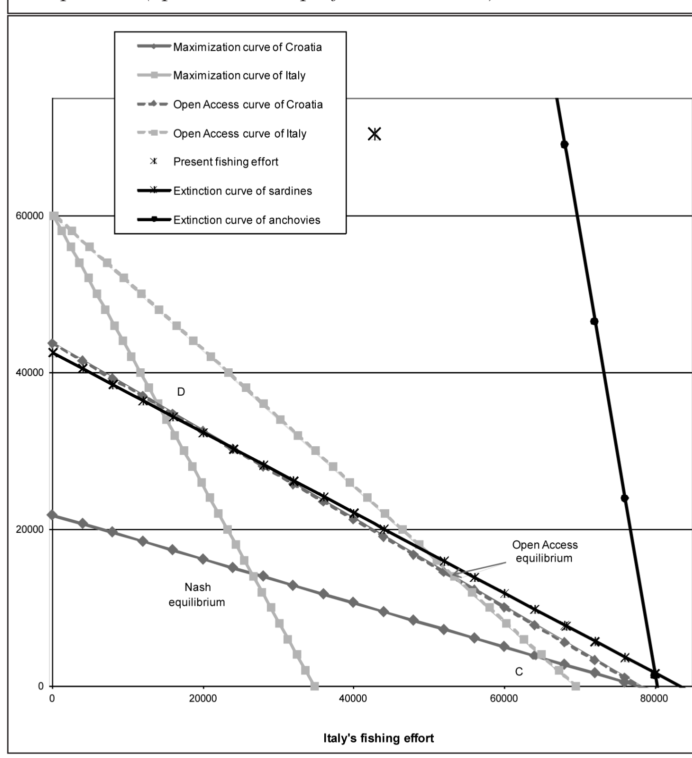
We will see the difference in steady-state fishing efforts due to different management options for the two fisheries. Figure 2 shows the steady stage solutions of the system assuming open access management and profit maximization management. The intersection of the reaction curves of the two fisheries identifies the open access equilibrium, the Nash equilibrium, and the other two equilibria obtained with mixed managements (points C and D). Furthermore, in the same chart, the two extinction curves of sardines and anchovies are included. It is maybe surprising to observe that the open access equilibrium, the Nash equilibrium, and equilibrium C lie under the sardines' extinction curve, while equilibrium D lies over the line. This result implies that sardines' extinction should not occur if both fisheries follow open access strategies, while it should happen if Croatia follows the open access strategy and Italy follows the profit maximization strategy. On the other hand, no problem should occur for anchovies.

In the same chart, the present fishing effort of both fisheries is observed. The figure seems to indicate that present fishing effort of Croatia is far beyond any bioeconomic equilibrium point. It is also worthwhile to note that the Croatian fishing effort corresponding to the open access equilibrium is lower than the fishing effort corresponding to the Nash equilibrium. On the contrary, the Italian fishing effort corresponding to the Nash equilibrium is lower than the open access equilibrium (roughly by half). The present Italian effort is between these two levels.

3.2. Sensitivity analysis

Conclusions seem particularly severe for the Croatian fishery because the model suggests that its fleet should drastically reduce in the future. As we will show, with some sen-

Figure 2. *Steady-state solutions for the Adriatic system assuming different policies (open access or profit maximization).*



[5] It is not surprising that prices of Croatian landings is higher than Italian prices because fish caught by purse seiners are of better quality than are the catches of pelagic trawlers (the same price variation can be seen for Italian purse seiners and pelagic trawlers). On the low price of small pelagics in Italy see also Cosmina *et al.* (2012) and Gaviglio and Demartini (2009).

sitivity analyses, these conclusions would be completely different with small changes in certain parameters. The different values that we will use in the sensitivity analysis can be interpreted as either inaccuracy of the present coefficients or changes due to exogenous causes.

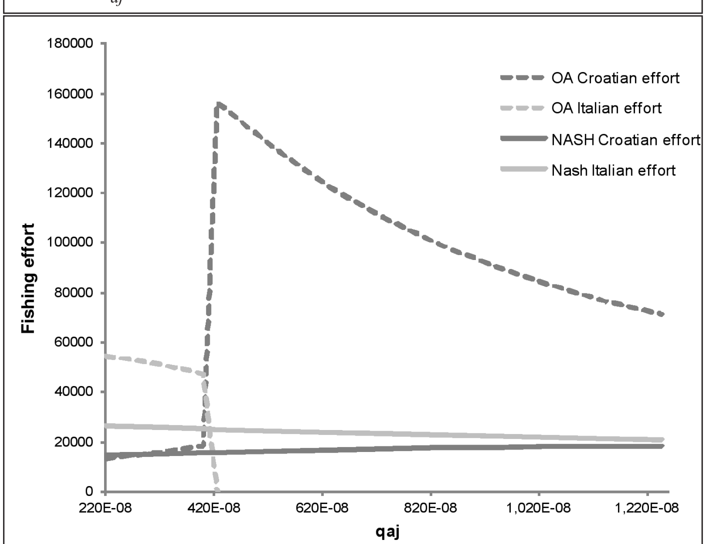
3.2.1. The Croatian catchability coefficients for anchovies (q_{aj})

In this study, we have assumed that the Croatian catchability coefficient (q_{aj}) for anchovies is lower than the Italian coefficient (2,21E-06 and 1,25E-05, respectively). In Figure 3, the steady-state effort levels (for the Nash and open access equilibria) shown in the case q_{aj} were higher, varying from the present level to the Italian level.

As expected, the Croatian steady-state effort increases with higher levels of q_{aj}, both in the theoretic open access equilibrium and in the theoretic Nash equilibrium. Under the open access assumption, with values of q_{aj} higher than 4.00E-06 (still far lower than Italian catchability), efficiency of the Croatian fleet is sufficiently high to cause the disappearance of the Italian fleet and, at the same time, the extinction of sardines (these effects are the consequence of the discontinuity of the reaction curves). Without the Italian competition, the steady-state effort of Croatia jumps to the open access level with a single fleet (and a single species), abundantly higher than the present Croatian fishing effort (160,500 versus 70,488 units of fishing effort, respectively).

On the contrary, steady-state efforts change more slowly in the Nash solution. The Italian fishing effort is almost unaffected, while the Croatian effort slowly increases close to the Italian levels.

Figure 3. *Steady- state effort, assuming open access (OA) or profit maximization (Nash) policies, and different Croatian catchability coefficients (q_{aj}) for anchovies*



3.2.2. The intrinsic growth rate of sardines (r_p)

The estimated intrinsic growth rate of sardines (r_p) is much lower than that of anchovies. The literature suggests that small pelagic dynamics are conditioned by unpredictable fluctuations in recruitment due to climatic changes. Recent studies show that in the last several years (2008-2010), recruitment has slightly increased (Santojanni *et al.*, 2011). This exogenous change can be included in a surplus production model that considers higher levels of *r*, as compared with the average intrinsic growth rate previously estimated. The Croatian steady-state effort would be positively affected by an augmented intrinsic growth rate of sardines under both assumptions of open access and Nash equilibria. On the other hand, the Italian effort would increase only in the case of Nash equilibrium (but less than the Croatian effort), while it would decrease (substituted by the Croatian effort) in the open access case.

3.3. Supply regimes

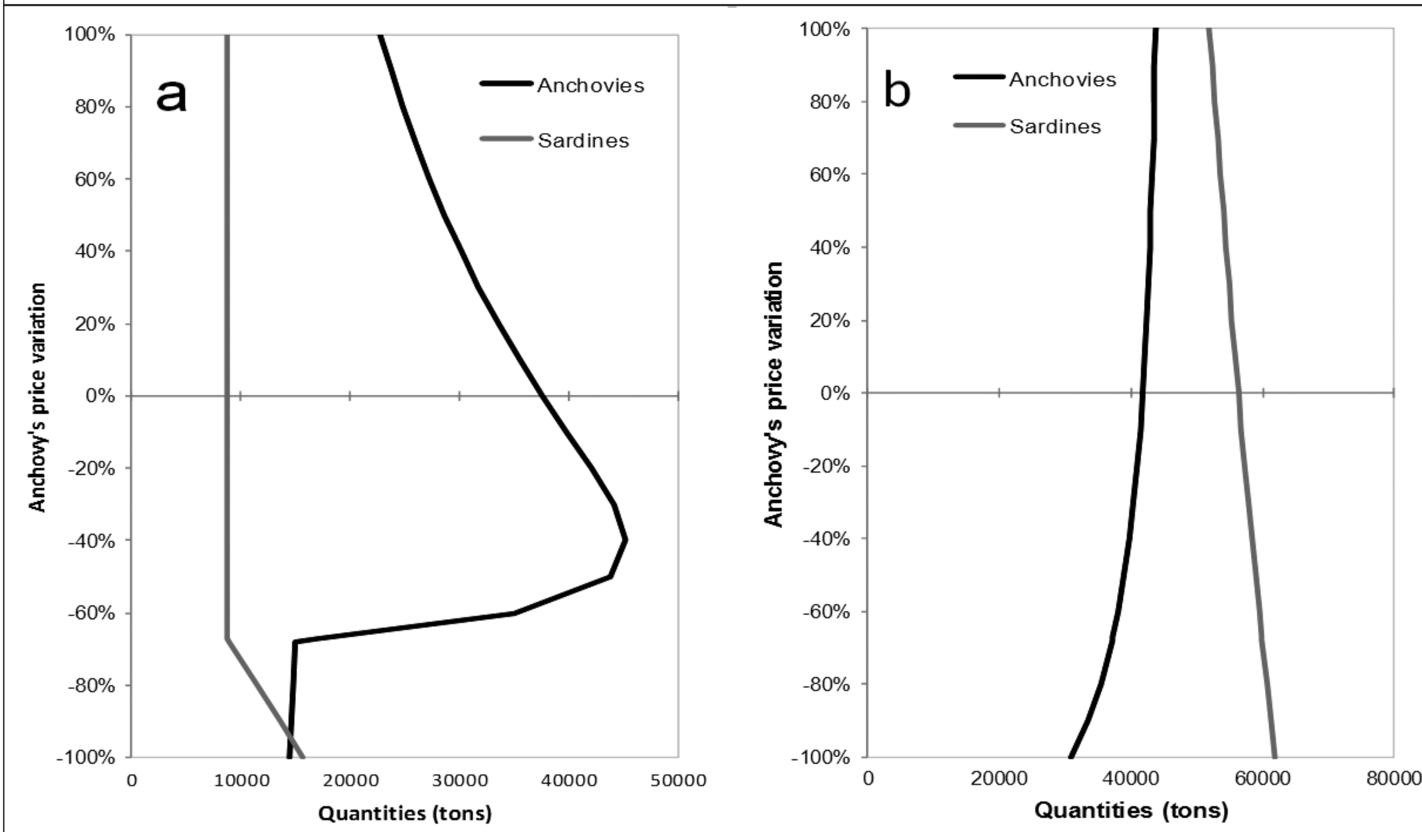
If we use a chart (Figure 4) to illustrate the changes in (steady-state) quantities due to changes in prices, we obtain a supply curve.

Anchovy price on the Italian market is conditioned by international demand and supply (Camanzi *et al.*, 2012; Mulazzani *et al.*, 2013). Demand and price have increased since 2005, when the fishery of anchovies was closed in the Bay of Biscay (because of the severe overexploitation of the stock) both for the Spanish and for the French fleets. The ban was lifted only in 2010 when a scientific evaluation showed good recovery of the stocks. Both the Italian and Croatian steady-state efforts would be affected by increases/decreases in p_a (we continue to assume that price of Croatian anchovies is double that of Italian anchovies). Obviously, steady-state catches of both anchovies and sardines would also be influenced by anchovy price. Figure 4 shows the total supply curves of anchovies and sardines (Italian and Croatian catches are added) with respect to anchovy price change. Figure 4a illustrates the equilibrium in the open access case; Figure 4b illustrates the supply curve for the profit maximization assumption.

In the open access case (Figure 4a), the anchovy supply curve assumes a shape that is close to the backward-bending supply curve, first described by Copes (1970) for a single fishery and a single target species. However, some peculiarities are manifest. A discontinuity is clearly visible when there is a -67% change in the anchovy price. At this point, the steady-state effort of the Italian fishery (rapidly decreasing with negative price variations) is zero. On the contrary, the Croatian steady-state effort increases when anchovy price decreases, taking advantage of the Italian exit from the fishery. For negative price changes higher than 67%, all catches are due to the Croatian fleet. Catches should theoretically continue also when price is zero: in this case, anchovies should be considered bycatches, while sardines should be considered the only target species.

Curiously, anchovy price changes affect the total sardine supply only after the disappearance of the Italian fishery occurs. For higher prices, the total steady-state supply does not change, but national shares do change, with Italian sardine catches positively influenced by higher anchovy prices.

Figure 4. *Total steady-state production (Italy and Croatia), assuming open access (on the left, a) or profit maximization (on the right, b) policies, and changes in the anchovy's price.*



Steady-state supply curves are different in the Nash framework (Figure 4b). First, it is possible to observe that with lower levels of fishing effort, sardines represent the most abundant catches. Second, there are no discontinuities due to the disappearance of any fishery (there is always a substitution of fishing effort favorable to the Croatian fleet when anchovy price decreases). The anchovy supply curve is close to the discounted supply curve (with a zero discount rate) described in the literature for a single fleet and a single target species (Clark, 1990). However, some macroscopic differences are clearly visible: above all, anchovies continue to be caught when the price is zero because they become bycatches of the sardine's fishery. Sardine steady-state supply is conditioned by anchovy price because higher prices cause increased fishing effort (mainly Italian fishing effort) and then lower sardine stock biomass.

4. Discussion and conclusions

In this paper, we have proposed a bioeconomic model to analyze strategic interaction between two players in the case of two target species. We have shown, theoretically and with a numerical application, how the steady state of the system is conditioned by exogenous bioeconomic variables and policy decisions. The economic exclusion of one player and/or the extinction of one species can easily occur because of small changes in the original conditions. Specifically, we have shown that complete replacement of a fleet, associated with the extinction of one species, can abruptly occur (in the steady- state framework) when the efficiency of one fleet becomes sufficiently higher than the efficiency of the other. More generally, elements such as prices, costs, technical (catchability) coefficients, and biological parameters all have an evident influence on the equilibrium of the system and can determine the relative predominance of one fleet (and one fish stock) over the other.

The management decisions of the two players also affect the definition of the bioeconomic system. In this work, we have examined two possible management objectives (or pressures), conditioning the choices of both players: the open access option and the profit maximization option. Players independently choose their objectives, and so mixed scenarios (one player choosing the open access management and the other one choosing the profit maximization objective) are also possible. The idea that one player, such as a public authority or a producers' organization, deliberately chooses an open access policy might seem irrational. It is well known that that this choice leads to complete rent dissipation. On the other hand, this situation is probably still very common for many different reasons. Open access, for example, could be unintentionally pursued if the scientific knowledge of the biological environment is poor, such that the management authority is unable to plan sustainable catches. Conversely, the management authority could be impelled by the fishermen to augment the fishing effort[6] allowed because short-term objectives are considered more important. In more extreme cases (e.g., marginal regions; fishermen that cannot be otherwise employed), it is not unreasonable to imagine that the fishing authority deliberately chooses an open access policy, knowing that this option leads to the overcapitalization of the fleet and, at the same time, to an increase of employment (we could say that open access produces the Maximum Sustainable Employment). Commonly, all these reasons (poor or unheeded scientific advice, short-term interests, social constraints) work together to determine management choices and results that are close to an open access situation.

This framework is potentially applicable to many Mediterranean fisheries such as the small pelagic Adriatic fishery, involving Italian and Croatian fleets. Although the time series data available for the Croatian fleet are of poor quality, it seems that fishing effort has increased considerably since the end of the 1990s. According to the Croatian Bureau of Statistics, the gross tonnage of the Croatian fleet is almost tripled from 1997 (most of the increase is from 1997 to 2003). This rapid growth does not seem justified by the state and the biologic possibilities of the small pelagic biomass, so that our bioeconomic model estimates the present Croatian fishing effort above the bioeconomic equilibrium in the case of pure open access policies (that is, the Italian authority also chooses the open access management option).

On the other hand, the poor quality of data suggests that caution be taken when considering these solutions. Sensitivity analyses show that slightly higher catchability coefficients (especially for anchovies) should lead the Croatian fleet to completely replace the Italian one. Other changes in the present conditions could favor the Croatian fishermen. In particular, there is evidence that sardine recruitment has recently slightly increased, while anchovy price should decrease in future. Because the Croatian fishery is more dependent on the sardine stock and the Italian fishery depends more on anchovies, this combination of elements entails a strong relative advantage for the Croatians.

Such exogenous changes in bieconomic parameters (prices, recruitment, technologies, etc.) prove that a long-run equilibrium will be never reached. Policies and management choices, such as public aids and incentives (and disincentives), also change. Thus, steady-state models simply illustrate the potential trends of the bioeconomic system rather than the exact solutions of a mathematical problem.

More consideration should be given to the catchability coefficient. One important reason to expect time variation in catchability is the technological progress. We have seen the consequences of a growth of the Croatian catchability coefficient for anchovies. If all catchability coefficients (for both species and fleets) grew proportionally, there should not be appreciable substitution between the two fleets (neither in the open access nor in the maximization profit option); on the other hand, neither a steady-state fishing effort nor a steady-state stock size should exist, both decreasing as the ability to find and catch fish improves (Squires and Vestergaard, 2009). This result explains why, in spite of measures that reduce fishing effort, fisheries and stocks are often in an open-access-like situation.

Catchability is conditioned not only by technology but also by fish behavior, such as schooling and vertical and horizontal displacements. Asymmetry in the stock density between two regions, as could be the case for east and west of the Adriatic, should be carefully considered in further investigations, especially if asymmetry is not constant over time.

For these and other issues, it is desirable that scientific cooperation between Italy and Croatia grow stronger, as it is expected with the accession of Croatia into the EU. In this paper, we have not addressed cooperative games. We assumed that management authorities could choose between open access and profit maximization. In both cases, there is no cooperation between the two players. This possibility could be considered in further research. On the other hand, cooperative decisions between Italy and Croatia could be difficult if time series data is used to allocate the fishing effort (or catches) quotas. Croatia could claim higher quotas because of the last decade's fleet (and catches) growth, while Italy could contest that recent Croatian fishing effort escalation is responsible of stock overexploitation.

In the Adriatic Sea basin, the regional authorities of Italy, Croatia and Slovenia are long collaborating to prepare a strategic agenda for the sustainable development of Adriatic fisheries. This program, despite the good intentions, is far to find application. Problems tied with multilevel governance and stakeholder participation are not easy to solve. Considering that the latest attempts of the European Commission to introduce transferable fishing concessions in the Common Fisheries Policy have been largely criticized by fishermen organizations, including the regional advisory body for the Mediterranean (RAC-MED), solutions to improve fisheries management seem to imply an increased involvement of interest groups, which also entails increased responsibilities in management decisions, direct contacts between fishermen and the scientific community, and increased participation of fishermen in management costs. Otherwise, if some sort of co-management is not launched, situation will hardly move from the current "State failure" conditions, where long-run solutions are normally sacrificed to short-term interests of both fishermen and politicians.

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[6] Or the TACs, for the fisheries where they are applied, but it is not the case of the Mediterranean Sea.

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