Marine Policy 53 (2015) 83–93

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Multi-criteria decision-making for fisheries management: A case study of Mediterranean demersal fisheries

Marisa Rossetto [a,b], Isabella Bitetto [c], Maria Teresa Spedicato [c], Giuseppe Lembo [c], Monica Gambino [d], Paolo Accadia [d], Paco Melià [a,b,*]

[a] Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, via Ponzio 34/5, 20133 Milano, Italy
[b] Consorzio Interuniversitario per le Scienze del Mare, Piazzale Flaminio 9, 00196 Roma, Italy
[c] COISPA Tecnologia & Ricerca, Stazione Sperimentale per lo Studio delle Risorse del Mare, Via dei Trulli 18/20, 70126 Bari, Italy
[d] NISEA Società Cooperativa, via Irno 11, 84135 Salerno, Italy

ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form
7 November 2014
Accepted 10 November 2014

Keywords:
Analytic hierarchy process
Decision support systems
Fisheries management
Mediterranean fisheries
Multi-attribute utility theory
Multi-criteria decision-making

ABSTRACT

A decision-making framework combining multi-attribute utility theory and the analytic hierarchy process is proposed to assess the performances of alternative fisheries management policies. The framework is demonstrated by applying it to a Mediterranean demersal fishery (GSA 18, Southern Adriatic Sea), for which a set of management scenarios are evaluated against their ability to cope with environmental, economic and social objectives. To this aim, (1) a suite of biological and socioeconomic indicators is identified and organized into an appropriate hierarchy; (2) a set of utility functions is defined to express the level of satisfaction associated with different values of the indicators; and (3) a set of weights, representing the relative importance of each indicator to the overall utility, is derived through a pair-wise comparison of the indicators. The proposed approach provides a practical decision-support tool to identify the management scenarios that are most desirable from the society's perspective, thus providing a good compromise between the environmental, economic and social aspects of the problem. The flexible structure of the framework allows the incorporation of different management criteria and utility functions to adapt it to different decision problems.

1. Introduction

Fisheries management handles typically with multidimensional problems. Decision-makers must often cope with multiple, and sometimes conflicting, objectives such as maximizing fishing yields and profits while minimizing ecological and social impacts [8,28,13]. In this respect, multi-criteria analysis [18] can provide a conceptual framework to support the decision process by allowing decision-makers to highlight possible trade-offs among conflicting viewpoints and to address a number of objectives that cannot be reduced to a single dimension such as the monetary one [4]. Despite it is widely agreed that the use of a multi-criteria approach is highly desirable [46], the use of multi-objective methods in fisheries research has been scarce over the past decades, although pioneering studies have been conducted since the early 1980s (e.g., [5,8]) and some recent examples can also be found in the literature (e.g., [44,32,29,3]). Nevertheless, most efforts remain directed to the development of analytical tools to evaluate the impact of management strategies from a single-objective perspective.

At the European level, the Common Fishery Policy 'shall ensure that fishing and aquaculture activities are environmentally sustainable in the long-term and are managed in a way that is consistent with the objectives of achieving economic, social and employment benefits, and of contributing to the availability of food supplies' ([9], Regulation no. 1380/2013), hence explicitly recognizing the inherent multidimensionality of fisheries management problems. In the Mediterranean basin, demersal species account for roughly 30% of total landings from the region, and represent therefore an important resource for the fishery sector [25]. However, strong concern exists regarding the long-term sustainability of demersal fisheries. Most demersal stocks targeted by the fisheries, including hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*), striped red mullet (*Mullus surmuletus*), blue and red shrimp (*Aristeus antennatus*), giant red shrimp (*Aristaeomorpha foliacea*), pink shrimp (*Parapenaeus longirostris*), and Norway lobster (*Nephrops norvegicus*), are currently fully exploited or overexploited [25,10]. Catches of demersal species in the Mediterranean have been increasing until the early 1990s, while they underwent a rapid decline thereafter [11]. In the last two decades, several species targeted by Mediterranean bottom fisheries have undergone significant reduction in size [7]. Achieving

* Corresponding author at: Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, via Ponzio 34/5, 20133 Milano, Italy. Tel.: +39 0223993680; fax: +39 0223993412.
E-mail address: paco.melia@polimi.it (P. Melià).

http://dx.doi.org/10.1016/j.marpol.2014.11.006

sustainability in the Mediterranean demersal fishery requires the urgent adoption of appropriate management strategies, which should not only make for the rebuilding of the stocks, but also aim at maintaining the economic profitability of the sector and avoid negative social impacts such as employment contraction. Sustainable fisheries management requires the development of tools to help decision-makers forecast the consequences of different management measures on the viability of fish stocks and on the socio-economics of fisheries, and bio-economic models are increasingly used to provide an integrated description of the coupled dynamics of natural resources and human welfare (see [33] for a review of Mediterranean applications). Nevertheless, little attention has been devoted so far to the development of tools specifically designed to assist decision-makers in the identification of conflicts and trade-offs among different management objectives.

In this study, a conceptual framework was developed to support a multi-criteria evaluation of alternative management scenarios. By combining different multi-criteria techniques, the proposed approach allows comparing alternative management scenarios on the basis of their ability to achieve a set of biological and socioeconomic goals. The analysis involves (1) the identification of appropriate biological and socioeconomic indicators and their organization into a proper hierarchy; (2) the definition of a set of mathematical functions to evaluate the satisfaction (utility) associated with each level of the different indicators; and (3) the determination of a set of weights that represent the relative importance of each indicator to the overall utility. The conceptual framework is demonstrated by applying it to a Mediterranean demersal fishery, that of the Southern Adriatic Sea, where all the stocks that have undergone a quantitative assessment so far have been evaluated as unsustainably exploited [12,42]. A sensitivity analysis is eventually performed to assess how uncertainty about the relative importance of the indicators affects the outputs of the multi-criteria analysis.

2. Methods

2.1. Study area and management scenarios

The multi-criteria decision-making framework presented in this study has been conceived to evaluate the performances of alternative fisheries management options on the basis of their potential impacts on selected environmental, economic and social indicators. The geographical subarea 18 (GSA 18) of the Adriatic Sea (central Mediterranean), as defined by the General Fisheries Commission for the Mediterranean (Fig. 1), was used as a case study. The area, which has an extension of 29,008 km^2, covers the Southern Adriatic Sea. The analysis focuses on the western (Italian) side of GSA 18, characterized by the presence of an important demersal fishery whose catches represent about 13% of the Italian fish production [7]. Trawling is the most significant fishing activity in the area, representing around 70% of the total effort; the most important target species include *M. barbatus*, *M. merluccius*, *N. norvegicus* and *P. longirostris* [7].

Ten management scenarios, aimed at reducing the fishing pressure on the stocks targeted by the demersal fishery and defined by different combinations of management measures, were assessed: changes in gear selectivity, reduction of fishing activity (i.e. limiting the number of days at sea), and reduction of fishing capacity (i.e. a partial decommissioning of the fishing fleet). Except for the first two, the objective of the management scenarios was to decrease the fishing mortality rate of the most vulnerable species among those targeted by the fishery, namely *M. merluccius*, or for the less vulnerable species, *N. norvegicus*. The target level for fishing mortality was set to the maximum sustainable yield (F_{MSY}) for the relevant species, while the time horizon over which the target level was to be attained was set to 5 or 10 years depending on the scenario. The resulting demographic dynamics were simulated over the period 2007–2021 for all four targeted species (*M. barbatus*, *M. merluccius*, *N. norvegicus* and *P. longirostris*). The main features of the explored management scenarios are summarized in Table 1.

Fig. 1. Geographical limits of GSA 18, as defined by the General Fisheries Commission for the Mediterranean.

Table 1
Fisheries management scenarios evaluated in this study.

Acronym	Short description	Target
SQ	*Status quo*	Maintaining current exploitation levels
CS	Changing gear selectivity	Increasing trawl mesh size from 40 to 60 mm
RD_10y	Reducing days at sea	Attaining F_{MSY} for *M. merluccius* in 10 years
RD_5y	Reducing days at sea	Attaining F_{MSY} for *M. merluccius* in 5 years
RV_10y	Reducing number of vessels	Attaining F_{MSY} for *M. merluccius* in 10 years
RV_5y	Reducing number of vessels	Attaining F_{MSY} for *M. merluccius* in 5 years
RDV_S1_10y	Reducing days at sea and vessels	Attaining F_{MSY} for *M. merluccius* in 10 years
RDV_S1_5y	Reducing days at sea and vessels	Attaining F_{MSY} for *M. merluccius* in 5 years
RDV_S2_10y	Reducing days at sea and vessels	Attaining F_{MSY} for *N. norvegicus* in 10 years
RDV_S2_5y	Reducing days at sea and vessels	Attaining F_{MSY} for *N. norvegicus* in 5 years

The biological and socio-economic effects of the different management scenarios were forecasted with BEMTOOL, a bio-economic modelling platform developed in the framework of the MAREA project (http://www.mareaproject.net) to inform and support the management of Mediterranean fisheries. BEMTOOL integrates a suite of models: assessment tools for the biological and management components include VIT [24], XSA [40], SURBA [31], ALADYM [21,41] and FLR scripts (http://flr-project.org), while models of the socio-economic component include functions from MEFISTO [26], BIRDMOD [1], FISHRENT [38], IAM [30], and BEMMFISH [33] models.

The BEMTOOL platform allows the forecast of how different harvesting and management strategies affect the dynamics of (1) the standing biomass and the demographic structure of a stock under exploited and unexploited conditions; (2) the main economic variables of the fishery; (3) fishing mortality and the related fishery outputs in terms of total production (landings and discards) and production by fleet segment; (4) the fishermen's behaviour, i.e. their investment/disinvestment decisions in the fishery (and its consequences on the fishing effort) as a response to changes in the profitability of the fishery itself. More details on the characteristics of the BEMTOOL platform are given in Section S1 of the Supplementary information.

2.2. Multi-criteria decision analysis

To assess the selected scenarios against multiple management objectives, a multi-criteria decision analysis (MCDA) was carried out by combining two multi-criteria techniques: multi-attribute utility theory (MAUT) and the analytic hierarchy process (AHP). MAUT relies on the idea that decision-makers attempt to maximize their utility with respect to a number of independent attributes [18], each one representing a management objective. Utility can be viewed as the level of desirability, or satisfaction, associated to a given value of a specific indicator [17]. When there are several attributes, the overall utility U (representing the overall satisfaction of the decision-maker with respect to the whole set of management objectives) is calculated as the weighted sum (assuming a fixed substitution rate between any two attributes) of the partial utilities u_i associated to the different attributes x_i:

$$U(x) = \sum_{i=1}^{n} w_i u_i(x_i) \tag{1}$$

where $u_i(x_i)$ (with $0 \le u_i \le 1 \ \forall i = 1, 2, \ldots, n$) is the utility associated to the value x_i taken by the i-th attribute, and w_i is the weight associated to the utility of the i-th attribute (subject to the constraint $\sum_{i=1}^{n} w_i = 1$). A commonly recognized critical point in the application of MAUT is the determination of the weighting set, because it is often difficult to grasp the preference structure of the decision-makers [2,14]. This problem was overcome by using the AHP [36,37], a method that facilitates the elicitation of individual preferences toward the different attributes and their conversion into a set of weights. The AHP is based on the decomposition of the decision problem into a hierarchy of smaller problems; then, pair-wise comparisons are performed on the elements of the hierarchy to build a pair-wise comparison matrix; the resulting matrix is eventually used to generate a vector of numerical priorities representing the relative weight (preference) of each decision element compared to the other.

To compare the selected scenarios (see Section 2.1) for the demersal fishery in GSA 18 within the above-described multi-criteria decision-making framework, the following steps were performed: (1) an appropriate suite of indicators was identified to represent the economic, social and biological objectives and organized into a hierarchical tree; (2) appropriate utility functions were designed to map each indicator into a measure of satisfaction; (3) the relative importance, or weight, of each indicator was calculated via the AHP.

2.2.1. Identification of socioeconomic and biological indicators

Evaluating fisheries management scenarios from a multidimensional perspective requires a suitable set of indicators. These have to be related to properties of the system that are relevant to the identified management objectives, non-redundant, and provide an unambiguous measure that can be compared with specific reference points to assess the achievement of the objectives. The choice of the indicators must also be based on their feasibility, i.e. the actual possibility to populate them under the specific scenarios to be evaluated and with the available forecasting tools. For the application to the selected case study, eight indicators (see Table 2) were selected among the output variables produced by the BEMTOOL platform, representing key attributes that are related to the sustainability of the fishery. These can be ascribed to four major categories of fisheries objectives to be maximized: economic efficiency, social wellbeing, biological conservation and biological productivity. For each indicator, relevant limit and/or target reference points (Table 2) were identified. Limit reference points indicate undesirable states of the fishery (or of a given stock) requiring management actions to avoid them, whereas target reference points indicate states that are desirable and at which management should aim [6].

With regard to the economic dimension, two indicators were selected – gross value added and the ratio of revenues to break-even revenue – to represent the objective of achieving economic sustainability. The gross value added (*GVA*) represents the added value that the fishery contributes to the economy; a value >0 means that the fishery is economically valuable. *GVA* can be interpreted as a measure of the long-term profitability of the sector. Although other indicators, like return on investment or net profit, are generally more suitable than *GVA* to measure profitability, their application to Mediterranean fisheries is often difficult. In fact, the low level of investments in Mediterranean fleets can produce unrealistic estimates of return of investment, while the coincidence between vessel owners and crew, which is habitual in small-scale fisheries, may impair a correct estimation of labour cost and, consequently, of net profit. The ratio of revenues to break-even revenue (*RBER*), instead, gives an indication of the economic sustainability of the fishing fleet

Table 2
List of socioeconomic and biological objectives (and relevant indicators) selected for the MCDA.

Objective	Indicator	Symbol	Limit reference point	Target reference point
Economic				
Maintaining profits in the long term	Gross value added	*GVA*		*MGVA*
Maintaining profits in the short term	Ratio of revenues to break-even revenue	*RBER*	>1	
Social				
Maintaining employment	Number of employees	*EMPL*		$\geq CE$
Maintaining job attractiveness	Average crew remuneration	*WAGE*		$\geq CW$
Biological conservation				
Avoiding overfishing	Fishing mortality	F	$2F_{MSY}$	0
Maintaining reproductive potential	Spawning stock biomass	*SSB*	$0.2SSB_0$	SSB_0
Biological production				
Maintaining fishing yield	Yield	Y		*MSY*
Reducing discard rates	Discard	D	*MD*	0

MGVA: maximum *GVA*; *CW*: current wage; *CE*: current employment; F_{MSY}: fishing mortality at maximum sustainable yield; SSB_0: spawning stock biomass in unexploited conditions ($F=0$); *MSY*: maximum sustainable yield; *MD*: maximum discard rate.

in the short-term [42]. The break-even point is defined as the point at which revenues equal fixed and variable costs. Hence, if the ratio is >1, revenues are enough to cover fixed and variable costs, indicating that the fishery is economically viable in the short-term. Conversely, if the ratio is <1, revenues are insufficient to cover fishing costs, indicating that the fishery is economically unviable.

As for social aspects, the two selected indicators were employment and wage. Employment (*EMPL*) is a key indicator of the social viability of a fishery and its maximization is among the most common objectives of fisheries management (e.g. [13]). Wage (*WAGE*) represents the average salary that the crew receives, and is another important component of social wellbeing (e.g. [39]).

The indicators selected to evaluate the conservation status of the exploited stocks were fishing mortality rate and spawning stock biomass. Fishing mortality rate (F) is an indicator of the harvest pressure on the stock. The most common target in fisheries management is achieving F_{MSY}, i.e. the rate of fishing mortality that ensures the maximum sustainable yield (see below). A fishing mortality rate above this threshold is indicative of overfishing. The spawning stock biomass (*SSB*) represents the portion of the stock that is able to spawn and allow the replacement of the dead individuals; in stocks subjected to a considerable fishing pressure, like Mediterranean ones, increasing levels of *SSB* are associated to increasing stock viability.

Fishing yield and discard rate were used to measure stock productivity. Yield (Y) indicates the amount of harvested fish (both landed and discarded); the biological target most commonly used in traditional fisheries management is the maximum sustainable yield (*MSY*), namely the maximum harvest that can be maintained in the long run without depleting the stock. Discard rate (D), calculated as the ratio between the amount of fish discarded and the total catch, is linked to the selectivity of the fishery and to technical management measures as the minimum conservation reference size.

Those eight indicators were organized into a hierarchical tree (Fig. 2), in which the global objective of ensuring fisheries sustainability is achieved through the accomplishment of the biological and socioeconomic objectives. The socioeconomic and biological objectives depend, in turn, on the lower-level specific criteria.

2.2.2. Definition of the utility functions

For each of the eight indicators, a utility function $u_i()$ was defined, i.e. a mathematical function mapping the value of each indicator i into a range comprised between 0 (minimum satisfaction with respect to that indicator) and 1 (maximum satisfaction). The utility function of each indicator was derived by identifying its range of variation, by determining the relevant functional form (monotonically increasing, decreasing, or non-monotone), and by defining the indicator values to be associated with minimum, maximum and/or intermediate levels of utility on the basis of limit and target reference points (Table 2).

2.2.3. Determination of the weight vector via AHP

Pair-wise comparisons were performed between indicators belonging to the same hierarchical level and for each level of the hierarchical tree. Here, a seven-point categorical scale was adopted to evaluate the relative importance of one indicator over the others: LLL (extremely less important); LL (less important); L (moderately less important); E (equally important); M (moderately more important); MM (more important); MMM (extremely more important). The categorical scale was mapped into the following numerical scale: MMM=7; MM=5; M=3; $E=1$; $L=1/3$; LL=1/5; LLL=1/7. Note that the scale used in this application is coarser than that originally proposed by Saaty [37], which includes 17 levels of preference (1–9 and the relevant reciprocals), to simplify as much as possible the interaction with experts and decision-makers.

The pair-wise comparisons were organized in a matrix form, in which the indicators on the rows were compared against those in the columns. According to the hierarchy of the decision elements, a total of seven comparison matrices, 2×2 in dimension, were defined. Two questionnaires were prepared (see Section S2 in the Supplementary information) and proposed to small panels of researchers from two collaborating institutions, IREPA and COISPA. IREPA promotes the research in fisheries economics and supports public bodies in fisheries management, while COISPA carries out applied research in the fields of marine science and natural resource management. The comparison among the indicators belonging to the top-level hierarchy was proposed to the experts of both groups. In contrast, the pair-wise comparisons among socioeconomic indicators were proposed only to the experts of IREPA, while those among biological indicators were proposed only to the experts of COISPA. As the primary objective was to illustrate a methodological framework, extensive stakeholder participation was not promoted in this evaluation exercise. The scores derived from the comparisons formed the elements of the upper hemi-matrix; the lower hemi-matrix was populated under the assumption of reciprocity, that is, if the score for indicator i compared to j was a_{ij}, then the score for indicator j compared to i should be $a_{ji}=1/a_{ij}$. The weight vector was calculated by normalizing the eigenvector corresponding to the dominant eigenvalue of the obtained matrix. To derive the final weighting set, local weights (expressing preferences among elements within a hierarchical level with respect to their parent

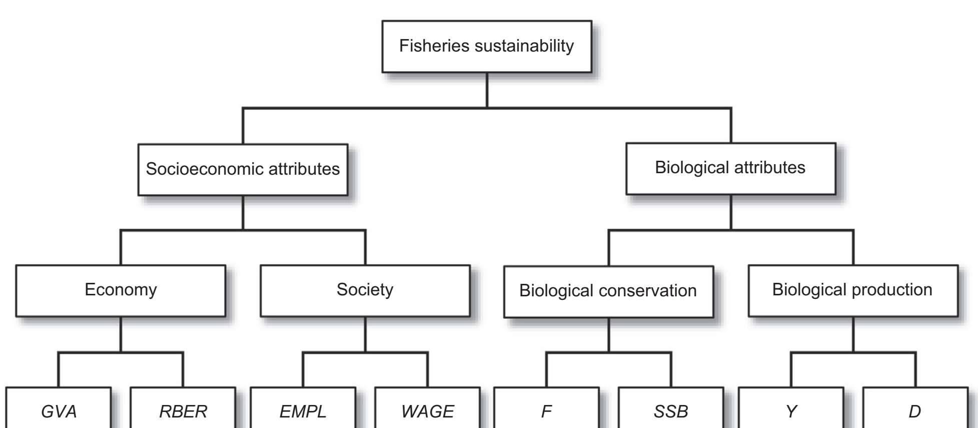

Fig. 2. Hierarchical tree of socioeconomic and biological indicators (see Table 2 for abbreviations) concurring to the sustainability of the fishery.

element in the upper level) were transformed into global weights by multiplying them by their parent's global weight. For instance, the global weight for *GVA* was calculated as the product of the relevant local weight (its relative preference against *RBER*), times the local weight of economic attributes (their relative preference against social ones), times the local weight of socioeconomic attributes (their relative preference against biological ones).

2.2.4. Assessment of the management scenarios

For each simulated management scenario, utilities were computed from the outputs corresponding to the last year of simulation (i.e. 2021). Biological conservation indicators (*F* and *SSB*) were produced for each of the four considered species. To obtain a single utility value (for each of the two indicators) from those relevant to the different stocks, the utility associated to the value of the indicator was first evaluated for each stock separately, and the four values were then aggregated through a geometric mean. Utility associated to biological production (*Y*) was instead computed aggregately for all species, i.e. on the basis of total yield. As for the selected case study the necessary information to parameterize and simulate discarded volumes was lacking, a default value of $D=0$ was assumed for all scenarios.

2.2.5. Sensitivity analysis

MCDA assessments are affected by a wide range of uncertainties, due to the intrinsic variability that characterizes all environmental systems, to the imperfect knowledge of the specific system under study, and to the subjectivity of expert judgements (see e.g. [35] for a review of sources of uncertainty and methods for their assessment). A sensitivity analysis was therefore carried out to evaluate the robustness of the results of the present analysis with respect to the uncertainty associated to the weights expressing the relative importance of the indicators used in the MCDA. To this end, we used the following Monte Carlo approach:

1. for each comparison between indicators at the lowest hierarchical level, we extracted (see Section 2.2.3) the relevant local weights from the pair-wise comparison matrix;
2. we perturbed each weight by multiplying it by $(1+\varepsilon)$, where ε is a random factor drawn from a normal distribution with mean$=0$ and standard deviation σ set so that 90% confidence bounds encompass the original value of the weight $\pm 25\%$ ($\sigma=0.15$);
3. we normalized the obtained weights in order to ensure that they add up to 1;
4. we repeated steps 1–3 for all comparisons at the same hierarchical level and for all levels;
5. we derived the global weight for each indicator as the product of local weights along the hierarchical tree.

The resulting weighting set was used to run the MCDA and rank the different scenarios. By repeating the random extraction a sufficient number of times, it was possible to associate an empirical probability distribution to the overall utility of each scenario. In this application, 1,000,000 extractions were performed to ensure an accurate estimate of distribution percentiles.

3. Results

3.1. Utility functions

3.1.1. Gross value added

GVA is a direct indicator of the economic profitability of the fishery. Therefore, the associated utility (u_{GVA}) should increase along with *GVA*; in contrast, marginal utility was assumed to decrease with increasing *GVA*. To represent this trend, an exponential curve was used:

$$u_{GVA} = a_{GVA}\left[1-\exp(-b_{GVA}\cdot GVA)\right] \tag{2}$$

To parameterize the curve, it was assumed that $GVA=0$ corresponds to a null utility, a *GVA* equal to its maximum level (*MGVA*) corresponds to a high utility (0.9), and a *GVA* equal to half *MGVA* (0.5*MGVA*) corresponds to an intermediate utility (0.5):

$$\begin{aligned} &u_{GVA}(0)=0\\ &u_{GVA}(MGVA)=0.9\\ &u_{GVA}(0.5MGVA)=0.5 \end{aligned} \tag{3}$$

Accordingly, parameters a_{GVA} and b_{GVA} were set (via the equations reported in Section S3 of the Supplementary information) to

$$\begin{aligned} &a_{GVA}=2.5\\ &b_{GVA}=0.446/MGVA \end{aligned} \tag{4}$$

3.1.2. Ratio of current revenues to break-even revenue

A value of *RBER* equal to one indicates that revenues equal fixed and variable costs, and provides therefore a limit reference point for this indicator, because a fleet with $RBER<1$ would work at a loss. Data from Italian demersal fisheries show that revenues are, on average, about 1.5 times the costs, a level that is considered acceptable in the fishery sector [15]. The relevant utility function (u_{RBER}) was expressed as an increasing sigmoid function:

$$u_{RBER} = 1/\left\{1+\exp\left[(RBER+a_{RBER})/b_{RBER}\right]\right\} \tag{5}$$

assigning a low utility (0.1) to $RBER=1$ and a relatively high utility (0.7) to $RBER=1.5$:

$$\begin{aligned} &u_{RBER}(1)=0.1\\ &u_{RBER}(1.5)=0.7 \end{aligned} \tag{6}$$

Parameters a_{RBER} and b_{RBER} were then set (see Section S3) to

$$\begin{aligned} &a_{RBER}=-1.361\\ &b_{RBER}=-0.164 \end{aligned} \tag{7}$$

3.1.3. Employment

To derive the utility u_{EMPL} associated to employment (*EMPL*), it was considered that social utility would strongly respond to changes around the current employment level (*CE*), while it would be less sensitive when employment is far below or beyond *CE*. This behaviour was described with an increasing sigmoid function:

$$u_{EMPL} = 1/\left\{1+\exp\left[(EMPL+a_{EMPL})/b_{EMPL}\right]\right\} \tag{8}$$

To parameterize the function, it was assumed that, when $EMPL=CE$, utility is intermediate (0.5), while for *EMPL* equal to half the current one (0.5*CE*) utility is very low (0.01):

$$\begin{aligned} &u_{EMPL}(CE)=0.5\\ &u_{EMPL}(0.5CE)=0.01 \end{aligned} \tag{9}$$

Accordingly, parameters a_{EMPL} and b_{EMPL} were set to

$$\begin{aligned} &a_{EMPL}=-1.001CE\\ &b_{EMPL}=-0.109CE \end{aligned} \tag{10}$$

3.1.4. Wage

The utility function u_{WAGE} for the average crew remuneration (*WAGE*) was modelled (under the hypothesis that individual utility increases with increasing levels of salary, but that marginal utility decreases) as an increasing exponential curve:

$$u_{WAGE} = 1-\exp(-b_{WAGE}\cdot WAGE) \tag{11}$$

It was assumed that $WAGE=0$ corresponds to a null utility and the current wage (CW) was associated to an intermediate utility (0.5):

$$u_{WAGE}(0)=0$$
$$u_{WAGE}(CW)=0.5 \quad (12)$$

Parameter b_{WAGE} was set (see Section S3) to

$$b_{WAGE}=0.693/CW \quad (13)$$

3.1.5. Fishing mortality

A common target reference point for fishing mortality (F) is the rate ensuring the maximum yield in the long term, F_{MSY}. In contrast, twice its value is considered a limit reference point, i.e. a level that should not be exceeded to avoid strong overexploitation [34]. Utility associated with fishing mortality (u_F) was described as a decreasing sigmoid function:

$$u_F=1/\{1+\exp[(F+a_F)/b_F]\} \quad (14)$$

For $F=F_{MSY}$, utility was assumed to be high (0.9); for values of $F>F_{MSY}$, utility decreases and approaches a low value (0.1) at $F=2F_{MSY}$. For values of $F<F_{MSY}$, utility remains high:

$$u_F(F_{MSY})=0.9$$
$$u_F(2F_{MSY})=0.1 \quad (15)$$

Parameters a_F and b_F were therefore set to

$$a_F=-1.5F_{MSY}$$
$$b_F=0.228F_{MSY} \quad (16)$$

3.1.6. Spawning stock biomass

It is commonly assumed that, to avoid recruitment overfishing, SSB should be maintained above 20–35% of the level that would occur in unexploited conditions, SSB_0. A review of Mace and Sissenwine [27] on 91 stocks from Europe and North America suggests that SSB should be maintained above 20% of the unexploited level on average, with some species requiring up to 40–60% of SSB_0 to avoid overfishing. Utility (u_{SSB}) associated to SSB was described via an increasing sigmoid function:

$$u_{SSB}=1/\{1+\exp[(SSB+a_{SSB})/b_{SSB}]\} \quad (17)$$

assuming that for $SSB=0.2\ SSB_0$ utility is very low (0.01), whereas at $SSB=SSB_0$ utility is very high (0.99):

$$u_{SSB}(0.2SSB_0)=0.01$$
$$u_{SSB}(SSB_0)=0.99 \quad (18)$$

Parameters a_{SSB} and b_{SSB} were accordingly set to

$$a_{SSB}=-0.6SSB_0$$
$$b_{SSB}=-0.087SSB_0 \quad (19)$$

3.1.7. Yield

Fishing yield (Y) is related to fishermen incomes. The associated utility function (u_Y) was described with an exponential curve analogous to that used for GVA:

$$u_Y=a_Y[1-\exp(-b_Y\cdot Y)] \quad (20)$$

To parameterize the curve, it was assumed that utility is null if $Y=0$, and high (0.9) if Y is equal to the maximum sustainable yield (MSY). An intermediate utility (0.5) was associated to a yield corresponding to half the MSY:

$$u_Y(0)=0$$
$$u_Y(MSY)=0.9$$
$$u_Y(0.5MSY)=0.5 \quad (21)$$

Accordingly, parameters a_Y and b_Y were set to

$$a_Y=2.5$$
$$b_Y=0.446/MSY \quad (22)$$

3.1.8. Discard rate

Decreasing discard rate (D), if achieved by improving gear selectivity, has strongly positive effects, as it allows releasing the target stock from useless exploitation and, at the same time, enhances the profitability of the fishing activity. The recent revision of the Common Fishery Policy ([9], Regulation no. 1380/2013), aiming to gradually eliminate discards, introduced the so-called "landing obligation", i.e. the obligation to land all catches of species subject to catch limits and/or minimum size. The landing obligation will be gradually introduced on a fishery-by-fishery base, with *de minimis* exemptions from the obligation for certain fisheries. To describe utility u_D associated to discard rate, a decreasing sigmoid

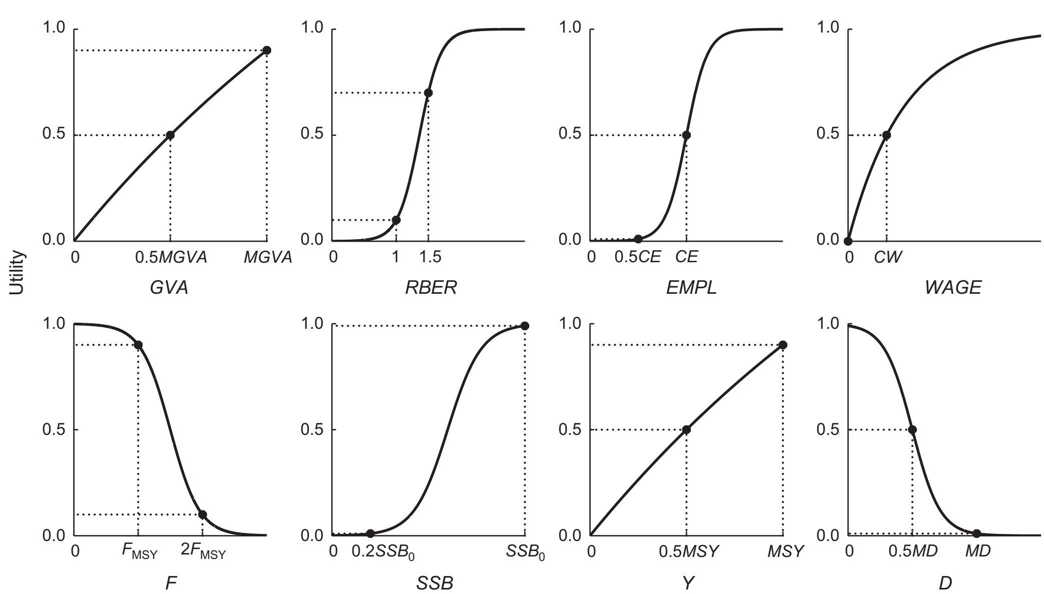

Fig. 3. Utility functions for the eight selected indicators (see Table 2 for abbreviations).

function was used:

$$u_D = 1/\{1+\exp[(D+a_D)/b_D]\} \tag{23}$$

assuming that utility is very low (0.01) for D equal to the maximum allowed discard rate (MD) and intermediate (0.5) for $D=0.5MD$:

$$u_D(MD) = 0.01$$
$$u_D(0.5MD) = 0.5 \tag{24}$$

Accordingly, parameters a_D and b_D were set to

$$a_D = -0.5MD$$
$$b_D = 0.109MD \tag{25}$$

In the present application, a maximum discard rate of 10% was considered. Utility functions for the eight selected indicators are shown in Fig. 3.

3.2. Utility weights from the analytic hierarchy process

When asked to compare management criteria at the top-level hierarchy (socioeconomic vs. biological objectives), the experts of both groups (economists and biologists) considered biological aspects to be more important than socioeconomic ones in order to maximize society's wellbeing. Accordingly, an overall weight equal to 0.69 was assigned to the set of biological criteria, and weight=0.31 was assigned to the socioeconomic criteria.

Between socioeconomic criteria, social aspects were judged more important (weight=0.83) than economic ones (0.17). Employment was deemed more important (0.75) than wage (0.25) between indicators of social performance, while between indicators of economic performance less importance (0.17) was given to the gross value added compared to the ratio of revenues to break-even revenue, which focuses on the short-term performance (0.83). Regarding biological criteria, indicators of biological conservation were considered to be more important (0.75) than those associated to productivity (0.25). Between biological conservation indicators, fishing mortality and spawning stock biomass were judged to be equally important. As for indicators of biological productivity, yield was evaluated as more important (0.79) than discard rate (0.21).

The final weights obtained for each indicator used in the analysis are reported in Table 3. Biological conservation indicators (spawning stock biomass and fishing mortality) have the largest weights (0.26), followed by employment (0.19) and yield (0.14). These four indicators account together for more than 85% of the overall weight.

Table 3
Final weights associated with the indicators (see Table 2) obtained through the analytic hierarchy process.

Indicator	Weight
GVA	0.01
RBER	0.04
EMPL	0.19
WAGE	0.06
F	0.26
SSB	0.26
Y	0.14
D	0.04

3.3. Results of the MCDA applied to the case study

The results of applying the MCDA to the ten management scenarios for GSA 18 (South Adriatic) are reported in Table S1 (Supplementary information) in terms of raw indicators and in Table 4 (summarized in Fig. 4) in terms of utility. Scenarios RD_5y and RD_10y (see Table 1 for acronyms) are associated with the highest values of overall utility (U equal to 0.57 and 0.52, respectively), whereas SQ, RDV_S2_10y and RDV_S2_5y are the worst performing scenarios (U=0.28).

The performances of the different scenarios vary widely depending on the different perspectives from which they are evaluated and that contribute to the overall utility. *GVA* does not show a large variability among scenarios and ranges between 52 M€ (for scenario RDV_S1_10y) and 74 M€ (for RV_5y), with the theoretical maximum being 136 M€. The rather narrow range of variation of the indicator is reflected in the values of the relevant utility, ranging between 0.39–0.54. *RBER*, in contrast, shows larger variation, varying between 1.08 (for CS) and 1.60 (for RV_5y) and determining a range of utility between 0.15 and 0.81.

Social indicators (wage and employment) undergo moderate variation across scenarios. Utility associated with wage ranges from 0.46 (for CS) to 0.76 (for RDV_S1_5y), with the first scenario implying a slight reduction in wage with respect to current level (−11%) and the latter a significant increase (more than twice the current level). As for employment, six out of ten scenarios would strongly reduce the number of employees below the current level; consequently, the relevant utility is very low (between 0.006 and 0.09). The remaining four scenarios produce a slight increase in the number of employees (+23) with respect to present (2314) by 2021, and have an associated utility=0.52.

Utility associated with fishing mortality exhibits marked variation among scenarios, ranging between 0.04–0.97. In particular, the lowest values are observed for scenarios SQ (0.04), CS (0.05), RDV_S2_10y and RDV_S2_5y (0.26), as these scenarios determine still excessively high mortality ($F > F_{MSY}$) for the four exploited fish stocks. The other six scenarios, instead, which aim to reduce the fishing mortality of *M. merluccius*, would ensure safe levels of F also for the other exploited stocks; therefore, a high utility value (0.97) is associated to these scenarios.

Scenarios SQ, CS, RDV_S2_5y and RDV_S2_10y fail to maintain *SSB* above 20% of the unexploited level for all the four exploited

Table 4
Performances (utility) of ten scenarios (see Table 1 for acronyms) for the management of demersal fisheries in GSA 18 assessed against 8 management objectives (see Table 2). The last row shows the overall utility (calculated as the weighted sum of the utilities associated to each indicator).

	SQ	CS	RD_10y	RD_5y	RV_10y	RV_5y	RDV_S1_10y	RDV_S1_5y	RDV_S2_10y	RDV_S2_5y
u_{GVA}	0.43	0.43	0.46	0.51	0.49	0.54	0.39	0.46	0.50	0.52
u_{RBER}	0.15	0.15	0.18	0.24	0.77	0.82	0.50	0.72	0.41	0.45
u_{EMPL}	0.52	0.52	0.52	0.52	0.01	0.01	0.01	0.01	0.09	0.09
u_{WAGE}	0.46	0.46	0.48	0.51	0.71	0.74	0.66	0.77	0.61	0.63
u_F	0.04	0.05	0.97	0.97	0.97	0.97	0.97	0.97	0.26	0.26
u_{SSB}	0.01	0.02	0.12	0.24	0.12	0.24	0.12	0.26	0.02	0.03
u_Y	0.66	0.67	0.46	0.52	0.46	0.52	0.47	0.52	0.65	0.68
u_D	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
U	0.28	0.29	0.52	0.57	0.47	0.51	0.45	0.51	0.28	0.28

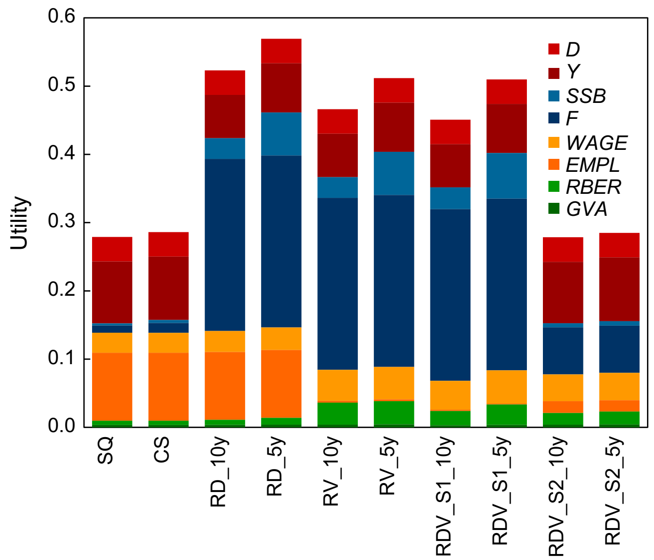

Fig. 4. (color online) Performances (utility) of ten scenarios (see Table 1 for acronyms and a brief description) for the management of demersal fisheries in GSA 18. Each colour represents the partial utility of the scenario with respect to a specific indicator (see Table 2 for abbreviations).

stocks (with *M. merluccius* being the most vulnerable species). Consequently, the corresponding utility is very low (<0.03). In contrast, the other six scenarios, which aim at achieving F_{MSY} for *M. merluccius*, have a higher utility value for *SSB* (0.12–0.26). In particular, scenarios designed to reduce mortality rates within 5 years show the highest utility for *SSB*, as they would maintain *SSB* above 30% of SSB_0 for all species.

All management scenarios are predicted to deliver a total yield between 45% and 71% of the *MSY*. The associated utility shows little variation among scenarios (range: 0.46–0.68). As the discard rate was always assumed to be zero during the forecast, the corresponding utility was the same for each scenario and equal to 1.

3.4. Sensitivity analysis

Fig. 5 shows the results of the sensitivity analysis. Although different scenarios have different average performances, the range of uncertainty (as obtained by Monte Carlo simulation) is quite similar for all scenarios (Fig. 5a). The frequency distribution of overall utility for the four best scenarios (RD_5y, RD_10y, RV_5y and RDV_S1_5y) is displayed in more detail in Fig. 5b, showing a moderate overlap between the frequency distribution of the scenario with the highest average performance (RD_5y) and those of the other three, whereas the distributions of the other scenarios are strongly overlapping. Fig. 5c shows the frequency with which each of the four best scenarios was assigned a different rank. Despite the existing overlaps, the ranking appears quite stable: in particular, RD_5y was ranked first in 100% of the cases, providing strong support to its designation as the best scenario.

3.5. Correlation among indicators and utilities

An explorative analysis was conducted to assess ex-post correlations (measured with Pearson's correlation coefficient) among raw indicators and among their associated utilities. For biological indicators (see Fig. S1 in the Supplementary information), correlation was evaluated both among the different indicators obtained for the same species and for the values of the same indicator obtained for the different target species. Within each single species, *F* is strongly positively correlated with *Y* and negatively correlated with *SSB*; a negative correlation is also evident between *Y* and *SSB* (Fig. S1a). Values of the same indicator calculated for the four species are strongly positively correlated among them. Indeed, values of *F*, *SSB* and *Y* show high and positive correlation across species (Fig. S1b–d).

As for socioeconomic indicators (Fig. S2), wage and employment are strongly negatively correlated. *RBER* is positively correlated with wage and negatively correlated with employment. The correlation among utilities (Fig. S3) reflects quite tightly the correlation among the relevant indicators, especially with respect to the absolute magnitude of the correlation coefficient. In some

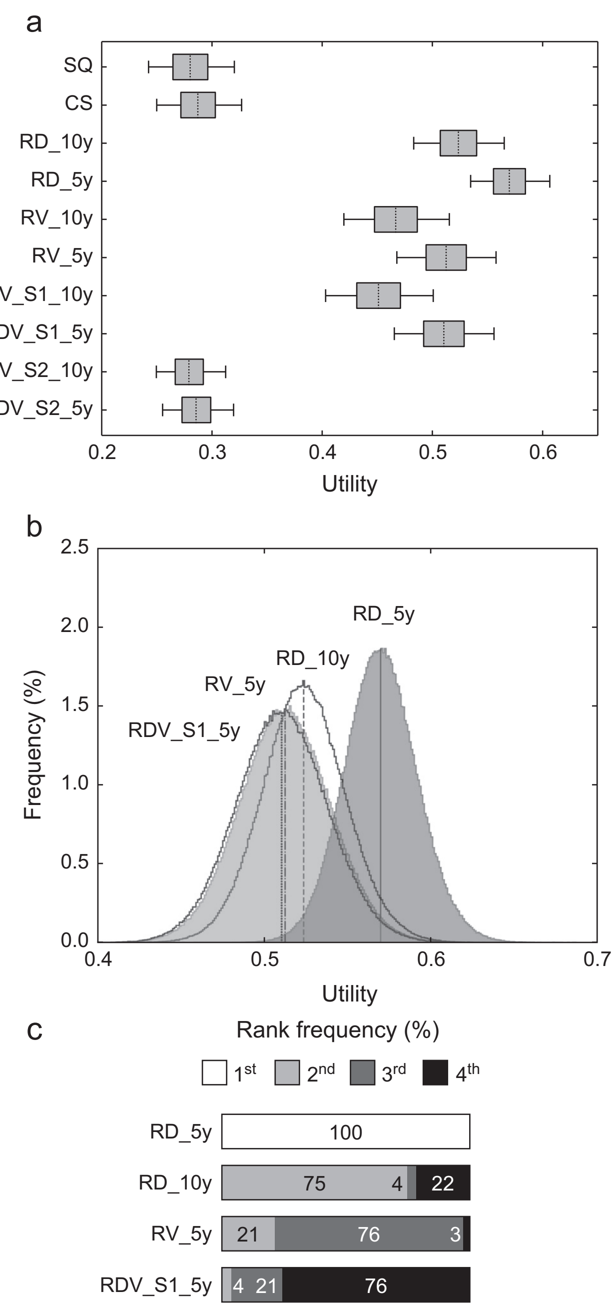

Fig. 5. Sensitivity of the estimated performances of different scenarios (see Table 1) with respect to uncertainty affecting the weighting set used in the multi-criteria analysis: (a) estimated variability of overall utility (dotted lines, shaded boxes and whiskers indicate median value, interquartile range and 90% confidence bounds, respectively) for each scenario; (b) empirical frequency distribution of overall utility for the best four scenarios; (c) frequency with which each scenario (among the best four) was assigned to the first four ranks.

cases, the correlation among utilities is opposite in sign compared to that among raw indicators, as a consequence of the utility functions adopted: for instance, F and Y are positively correlated (higher fishing pressure ensures higher harvests, at least in the short or medium term), whereas the associated utilities are negatively correlated (high yields are always well performing, whereas a high fishing mortality is associated with a low utility as it poses stocks at risk of overfishing).

4. Discussion

The decision-making framework developed in the present study combines two different multi-criteria techniques (MAUT and AHP) to support fisheries assessment with respect to multiple objectives. The proposed approach allows a direct, straightforward comparison of the performances of different fisheries management scenarios with respect to multiple criteria, providing a practical decision-support tool to highlight conflicts among fisheries management objectives, explore possible trade-offs and identify the management options that are most desirable from the society's perspective.

The decision-making framework was demonstrated by applying it to the management of a Mediterranean demersal fishery (GSA 18, Southern Adriatic Sea). The analysis was carried out on the outputs of a bio-economic modelling platform, BEMTOOL, developed in the framework of the MAREA project and aimed to forecast the dynamics of a large number of biological, social and economic variables under different management options. Among those variables, a small subset of indicators (8 in total) was selected with the aim to represent the different biological conservation and socio-economic goals. The number of indicators was maintained as small as possible to facilitate the interpretation of the results and to minimize redundancy and/or correlation. Utility functions were then defined to map each indicator into a 0–1 scale measuring the satisfaction with respect to the relevant management objective using simple yet flexible functional forms (exponential and sigmoid curves). Whereas exponential utility curves have been often used in multi-attribute analyses, given their flexibility to assume concave, convex, decreasing or increasing shapes (e.g. [17,45]), sigmoid utility curves are still relatively uncommon in the field of fisheries, although they are gaining popularity thanks to their ability to represent changes in the natural human propensity to risk across the range of variation of an attribute [19].

Although in recent years both MAUT and AHP have been applied to support the decision-making process in the field of fisheries research (e.g. [22,16,14,39]), the two techniques have been traditionally used separately and, to our knowledge, there is no example of combined applications of the two in this field. In this study, MAUT was used along with AHP to overcome one of the major criticalities in the application of MAUT, i.e. deriving individual preferences for one objective over another and transforming them into a vector of weight representing the relative importance of the different objectives.

AHP is not exempt from critical points: one of these is the possible emergence of inconsistencies as the weighting set is derived through a series of pair-wise comparisons. When more than 2 objectives are compared, consistency (i.e. the transitivity of the judgements quantifying the decision-maker preferences across all the elements being compared) is not guaranteed [37]. In the present application, pair-wise comparison matrices were always 2×2 (due to the dichotomous structure of the hierarchical tree, see Fig. 2), hence assuring consistency by definition. In more complex AHP applications, it can be useful to test if pair-wise comparison matrices have an acceptable level of consistency (see e.g. [20,23] for alternative approaches).

When applying the multi-criteria decision-making framework to the case of GSA 18, preferences were determined by the experts interviewed and not by a stakeholder panel. This might have substantially affected the judgement, giving a remarkable importance to the objective of improving biological conservation; in fact, spawning stock biomass and fishing mortality contributed together to more than 50% of the total weight assigned to the attributes (see Table 3). As most demersal stocks in the Mediterranean are currently severely overfished [42], it is not surprising that decreasing fishing pressure and supporting the recovery of the stocks are perceived as fundamental prerequisites to ensure the future viability of these fisheries. Other published applications of the AHP to the management of vulnerable fisheries also report that biological objectives are ranked as much more important than economic ones in determining the relative desirability of alternative fisheries management options (e.g. [22]). These outcomes may underline a growing awareness of the importance of maintaining healthy fish stocks (for both biological conservation and socioeconomic purposes) and avoiding over-exploitation (e.g. [43]). In the selected case study, employment was also assigned a high importance – almost one-fourth of the total weight. The ongoing contraction in the number of employees in the Italian fishery sector [15] may be one of the factors that determined the high importance given to employment. A relatively high weight was also assigned to yield (0.14), suggesting that maintaining a high biological productivity could be a desirable objective from the society's perspective. Instead, a low weight was assigned to economic indicators (*GVA* and *RBER* accounted together for 5% of the total weight), indicating that, although clearly desirable, economic efficiency was considered less important by the interviewed experts.

From the analysis, it emerged that scenarios aiming at achieving F_{MSY} for *M. merluccius* (RD_10y, RD_5y, RV_10y, RV_5y, RDV_S1_10y and RDV_S1_5y) perform much better (overall utility ranging between 0.45–0.57) than those not explicitly targeting the conservation of this overharvested stock (scenarios SQ, CS, RDV_S2_10y and RDV_S2_5y, utility ranging around 0.28). This suggests that policies aimed at reducing mortality rates of the most vulnerable species can achieve a high level of performance in the short run, in particular with regards to the biological conservation indicators, ensuring the concomitant protection of all exploited stocks. It is worth noting that F and SSB are given the major importance among the indicators selected in the analysis, jointly accounting for more than 50% of the total weight; therefore, the achievement of the conservation objectives is decisive in determining the overall performance of a specific scenario. As explained above, however, a different weighing set, reflecting a different perception about the relative importance of the different indicators by a more comprehensive stakeholder panel might have determined different results. Among the scenarios predicted to successfully avoid overfishing, the best performing one is RD_5y, which envisages the reduction of fishing mortality of *M. merluccius* within a 5-years horizon. Scenario RD_5y presents two main advantages: firstly, the fast reduction of fishing mortality for the most vulnerable target species, achieved on a short time scale, maximizes the recovery of spawning stock biomass; secondly, the reduction of fishing mortality obtained through a reduction of the number of days at sea allows sustaining employment above the current level (see Table S1). Decreasing effort by reducing the number of days at sea, rather than permanently withdrawing vessels, contributes to the overall utility by maintaining employment (the third most important indicator) at an acceptable level from the social point of view.

The analysis of correlation among indicators revealed the presence of several conflicts among objectives. In particular, negative correlations exist between yield and spawning stock biomass and between wage and employment. Conflict between conservation and production objectives is typical in fisheries management, and the conflict between wage and employment can hinder the achievement of a fully satisfactory social policy. In these cases, the relative weight associated to the several indicators is crucial to determine which objectives are predominant in determining the final trade-off, making the outcomes of the MCDA sensitive to the groups of interest involved in the decision-making process. The full consideration of all possible stakeholder perspectives was beyond the scope of the present application; although the results of the sensitivity analysis (Fig. 5) show that MCDA outputs are robust with respect to a moderate level of uncertainty affecting the weighting set, the involvement of a broad range of groups of interest may substantially impact the outcomes of the analysis. The flexible structure of the proposed approach easily allows the incorporation of additional criteria and the definition of other utility functions to fit a wider range of decision problems.

Acknowledgements

The useful comments of an anonymous reviewer helped us to improve the manuscript. This work was funded by the European Commission, Directorate General for Maritime Affairs and Fisheries, under Specific Contract no. 4-SI2.613770 (total amount paid by the European Union: 258,840 Euros), implementing the Framework Contract "Scientific advice and other services for the implementation of the Common Fisheries Policy in the Mediterranean" (MAREA Project, Contract no. MARE/2009/05-Lot 1). The opinions expressed in this article are those of the authors only and do not represent the Commission's official position.

Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2014.11.006.

References

[1] Accadia P, Spagnolo M. A bio-economic simulation model for the Italian fisheries. In: Proceedings of the Thirteenth Biennial Conference of the International Institute of Fisheries Economics & Trade (IIFET), July 11–14, 2006, Portsmouth, UK. Corvallis, Oregon: The International Institute of Fisheries Economics & Trade; 2006.
[2] Andalecio M. Multi-criteria decision models for management of tropical coastal fisheries. A review. Agron Sustain Dev 2010;30:557–80. http://dx.doi.org/10.1051/agro/2009051.
[3] Bevacqua D, Melià P, Crivelli AJ, Gatto M, De Leo GA. Multi-objective assessment of conservation measures for the European eel (*Anguilla anguilla*): an application to the Camargue lagoons. ICES J Mar Sci 2007;64:1472–82. http://dx.doi.org/10.1093/icesjms/fsm126.
[4] Bevacqua D, Melià P, Crivelli AJ, Gatto M, De Leo GA. Assessing management plans for the recovery of the European Eel: a need for multi-objective analyses. Am Fish Soc Symp 2009;69:637–47.
[5] Bishop R, Bromley DW, Langdon S. Implementing multiobjective management of commercial fisheries: a strategy for policy-relevant research. In: Anderson LG, editor. Economic analysis for fisheries management plans. Ann Arbor, Michigan: Ann Arbor Science; 1981.
[6] Caddy JF, Mahon R. Reference points for fisheries management. FAO Fisheries Technical Paper 347. Rome: FAO; 1995.
[7] Cataudella S, Spagnolo M, editors. The state of Italian marine fisheries and aquaculture. Rome: Ministero delle Politiche Agricole, Alimentari e Forestali; 2011.
[8] Charles AT. Bio-socio-economic fishery models. Labor dynamics and multi-objective management. Can J Fish Aquat Sci 1989;46:1313–22. http://dx.doi.org/10.1139/f89-169.
[9] EC. Regulation (EU) No. 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. Official Journal of the European Union. L 354:22-61 http://dx.doi.org/10.3000/19770677.L_2013.354.eng; 2013.
[10] FAO. Review of the state of world marine fishery resources. FAO fisheries and aquaculture technical paper No. 569. Rome: FAO; 2011.
[11] Garcia SM. Long-term trends in small pelagic and bottom fisheries in the Mediterranean: 1950–2008. Plan Bleu, Valbonne; 2011.
[12] GFCM. Report of the working group on stock assessment of demersal species. Split, Croatia, 5–9 November 2012. Rome: General Fisheries Commission for the Mediterranean; 2012.
[13] Hilborn R. Defining success in fisheries and conflicts in objectives. Mar Policy 2007;31:153–8. http://dx.doi.org/10.1016/j.marpol.2006.05.014.
[14] Innes JP, Pascoe S. A multi-criteria assessment of fishing gear impacts in demersal fisheries. J Environ Manag 2010;91:932–9. http://dx.doi.org/10.1016/j.jenvman.2009.11.011.
[15] IREPA. Osservatorio economico sulle strutture produttive della pesca marittima in Italia 2010. Napoli: Edizioni Scientifiche Italiane; 2010.
[16] Johnston FF, Arlinghaus R, Dieckmann U. Diversity and complexity of angler behaviour drive socially optimal input and output regulations in a bioeconomic recreational-fisheries model. Can J Fish Aquat Sci 2010;67:1507–31. http://dx.doi.org/10.1139/F10-046.
[17] Keeney RL. A utility function for examining policy affecting salmon on the Skeena River. J Fish Res Board Can 1976;34:49–63. http://dx.doi.org/10.1139/f77-006.
[18] Keeney RL, Raiffa H. Decisions with multiple objectives: preferences and value tradeoffs. Cambridge & New York: Cambridge University Press; 1993.
[19] Kuznar LA, Frederick WG. Environmental constraints and sigmoid utility: implications for value, risk sensitivity, and social status. Ecol Econ 2003;46:293–306. http://dx.doi.org/10.1016/S0921-8009(03)00167-8.
[20] Lane EF, Verdini W. A consistency test for AHP decision makers. Decis Sci 1989;20:575–90. http://dx.doi.org/10.1111/j.1540-5915.1989.tb01568.x.
[21] Lembo G, Abella A, Fiorentino F, Martino S, Spedicato M-T. ALADYM: an age and length-based single species simulator for exploring alternative management strategies. Aquat Living Resour 2009;22:233–41. http://dx.doi.org/10.1051/alr/2009024.
[22] Leung P, Muraoka J, Nakamoto ST, Pooley S. Evaluating fisheries management options in Hawaii using analytic hierarchy process (AHP). Fish Res 1998;36:171–83. http://dx.doi.org/10.1016/S0165-7836(98)00097-6.
[23] Lin C, Kou G, Ergu D. A statistical approach to measure the consistency level of the pairwise comparison matrix. J Oper Res Soc 2014;65:1380–6. http://dx.doi.org/10.1057/jors.2013.92.
[24] Lleonart J, Salat J. VIT: software for fishery analysis. User's manual. FAO computerized information series (fisheries) no. 11. Rome: FAO; 1997.
[25] Lleonart J, Maynou F. Fish stock assessments in the Mediterranean: state of the art. Sci Mar 2003;67(Suppl. 1):S37–49.
[26] Lleonart J, Maynou F, Recasens L, Franquesa R. A bioeconomic model for Mediterranean Fisheries, the hake off Catalonia (Western Mediterranean) as a case study. Sci Mar 2003;67(Suppl. 1):S337–51.
[27] Mace PM, Sissenwine MP. How much spawning per recruit is enough? In: Smith SJ, Hunt JJ, Revered D, editors. Risk evaluation and biological reference points for fisheries management. Canadian special publication of fisheries and aquatic sciences 120. National Research Council of Canada; 1993. p. 101–18.
[28] Mardle S, Pascoe S. A review of applications of multiple-criteria decision-making techniques to fisheries. Mar Resour Econ 1999;14:41–63.
[29] Melià P, Gatto M. A stochastic bioeconomic model for the management of clam farming. Ecol Model 2005;184:163–74. http://dx.doi.org/10.1016/j.ecolmodel.2004.11.011.
[30] Merzereaud M, Macher C, Bertignac M, Fresard M, Le Grand C, Guyader O, Daures F, Fifas S. Description of the Impact Assessment bio-economic Model for fisheries management (IAM). AMURE Publications. Working papers series no. D-29-2011; 2011.
[31] Needle CL. Survey-based assessments with SURBA. Working Document to the ICES Working group on methods of fish stock assessment, Copenhagen; 2003.
[32] Pan ML, Leung PS, Pooley SG. A decision support model for fisheries management in Hawaii: a multilevel and multiobjective programming approach. N Am J Fish Manag 2001;21:293–309. http://dx.doi.org/10.1577/1548-8675(2001)021 < 0293:ADSMFF > 2.0.CO;2.
[33] Prellezo R, Accadia P, Andersen JL, Andersen BS, Buisman E, Little A, Nielsen JR, Poos JJ, Powell J, Röckmann C. A review of EU bio-economic models for fisheries: the value of a diversity of models. Mar Policy 2012;36:423–31. http://dx.doi.org/10.1016/j.marpol.2011.08.003.
[34] Punt AE. Extinction of marine renewable resources: a demographic analysis. Popul Ecol 2000;42:19–27. http://dx.doi.org/10.1007/s101440050005.
[35] Refsgaard JC, van der Sluijs JP, Højberg AL, Vanrolleghem PA. Uncertainty in the environmental modelling process – a framework and guidance. Environ Model Softw 2007;22:1543–56. http://dx.doi.org/10.1016/j.envsoft.2007.02.004.
[36] Saaty TL. A scaling method for priorities in hierarchical structures. J Math Psychol 1977;15:234–81.
[37] Saaty TL. The Analytic Hierarchy Process: planning, priority setting, resource allocation. New York: McGraw-Hill; 1980.
[38] Salz P, Buisman E, Frost H, Accadia P, Prellezo R, Soma K. ISHRENT. Bio-economic simulation and optimization model for fisheries. The Hague: LEI; 2011 (LEI report 2011-024).
[39] Seung C, Zhang CI. Developing socioeconomic indicators for fisheries off Alaska: a multi-attribute utility function approach. Fish Res 2011;112:117–26. http://dx.doi.org/10.1016/j.fishres.2011.04.004.
[40] Shepherd JG. Extended survivors analysis: an improved method for the analysis of catch-at-age data and abundance indices. ICES J Mar Sci 1999;56:584–91. http://dx.doi.org/10.1006/jmsc.1999.0498.
[41] Spedicato M-T, Poulard JC, Politou CY, Radtke K, Lembo G, Petitgas P. Using the ALADYM simulation model for exploring the effects of management scenarios of fish population metrics. Aquat Living Resour 2010;23:153–65. http://dx.doi.org/10.1051/alr/2010015.

[42] STECF. Report of the Scientific, Technical and Economic Committee for Fisheries (STECF). 2013 Assessment of Mediterranean Sea stocks part I (STECF 13-22). Luxembourg: Publications Office of the European Union; 2013.
[43] Sumaila UR, Cheung W, Dyck A, Gueye K, Huang L, Lam V, Pauly D, et al. Benefits of rebuilding global marine fisheries outweigh costs. Plos One 2012;7: e40542. http://dx.doi.org/10.1371/journal.pone.0040542.
[44] Sylvia G, Enríquez-Andrade RR. Multiobjective bioeconomic analysis: an application to the Pacific whiting fishery. Mar Resour Econ 1994;9:311–28. ⟨http://www.jstor.org/stable/42629090⟩.
[45] Utne IB. Are the smallest fishing vessels the most sustainable? – trade-off analysis of sustainability attributes Mar Policy 2008;32:465–74. http://dx.doi.org/10.1016/j.marpol.2007.09.016.
[46] Vaca-Rodriguez JG, Enríquez-Andrade R. Analysis of the eastern Pacific yellowfin tuna fishery based on multiple management objectives. Ecol Model 2006;191:275–90. http://dx.doi.org/10.1016/j.ecolmodel.2005.04.025.