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Common sole in the northern and central Adriatic Sea: Spatial management scenarios to rebuild the stock

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ABSTRACT

The northern and central Adriatic Sea represents an important spawning and aggregation area for common sole (*Solea solea*) and provides for around 20% of the Mediterranean landings. In this area, this resource is mainly exploited with *rapido* trawl and set nets. The stock is not yet depleted and faces a situation of growth overfishing. The comparison between the spatial distribution by age of *S. solea* and the geographic patterns of the *rapido* trawl fishing effort evidenced an overlapping of this fishing activity with the area where juveniles concentrate (age groups 0–2). The majority of spawners inhabits specific offshore areas, here defined as 'sole sanctuaries', where high concentrations of debris and benthic communities make difficult trawling with *rapido*.

The aim of this study was to evaluate existing spatial management regimes and potential new spatial and temporal closures in the northern and central Adriatic Sea using a simple modelling tool. Two spatial simulations were carried out in order to verify the effectiveness of complementary methods for the management of fisheries: the ban of *rapido* trawling from October to December within 6 nautical miles and 9 nautical miles of the Italian coast. The focus of the simulation is that the effort of the *rapido* trawl is moved far from the coast during key sole recruitment periods, when the juveniles are moving from the inshore nursery area toward the offshore feeding grounds. The management scenarios showed that a change in selectivity would lead to a clear increase in the spawning stock biomass and an increase in landings of *S. solea* in the medium-term. The *rapido* trawl activity could be managed by using a different logic, bearing in mind that catches and incomes would increase with small changes in the spatial pattern of the fishing effort.

The present study highlights the importance of taking into account spatial dimensions of fishing fleets and the possible interactions that can occur between fleets and target species, facilitating the development of control measures to achieve a healthy balance between stock exploitation and socio-economic factors.

1. Introduction

The fishery resources of the Mediterranean Sea and in particular of Adriatic Sea are under considerable and increasing stress from human activities. In both basins, the combined effects of fishing mortality and habitat degradation have led to alarming reductions of many exploited stocks (Barausse et al., 2011; Coll et al., 2009; Colloca et al., 2013; Russo et al., 2013).

In the northern and central Adriatic Sea flatfish resources are highly vulnerable to certain fishing activities (e.g. *rapido* trawling; Pranovi et al., 2000) and to anthropogenic impacts, such as the presence of contaminants and disruption to sea-floor integrity (e.g. dredging for beach

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nourishment). Within the group of flatfish, the common sole, *Solea solea* (Linnaeus, 1758), is one of the most commercially important species in the Adriatic Sea, that contributes around 23% to the overall sole catch of the FAO-GFCM (Food and Agriculture Organization-General Fisheries Council for the Mediterranean) area (Mediterranean and Black Sea; FAO-FISHSTAT source). The majority of this contribution is provided by the northern and central parts of the Adriatic basin where around 64% of the common sole catch come from the Italian *rapido* trawl fleets, 33% from the Italian, Slovenian and Croatian set netters operating mostly within 3 nautical miles from the coast, and the remaining 3% from the Italian otter trawlers (Grati et al.,2013). In particular, approximately 80% of sole *rapido* trawl landings in the area occur during the fall season (Fabi et al., 2009).

Considering the problem from population dynamic and fishery management perspectives, the case of *S. solea* in the northern and central Adriatic Sea is clearly the expected result of a defective management. The young portion of the stock continues to be exploited at unsustainably high levels (Scarcella et al., 2012) particularly in areas where juveniles aggregate and the use of alternative catch strategies could result in greater revenues than those currently generated (Colloca et al., 2013). Multiple assessment approaches used to analyse the health of the sole stock indicated clear overexploitation with extremely high fishing mortality (Scarcella et al., 2012). In the last decade, international working groups (in the framework of EC-STECF and FAO-GFCM) have recommended reducing fishing mortality by 80% as well as the development of a management plan to achieve this reduction over time. Considering the extraordinary stresses on both the structure and function of the northern and central Adriatic Sea habitat and the large overcapacity of the Italian fishing fleet, new management approaches are required. In such view, Colloca et al. (2013), proposed a L_{opt} for sole, a target reference point for catches that avoids the risks of growth and recruitment overfishing, as in the classical formulation by Beverton and Holt (1957) and Beverton (1992). Furthermore, the truncated age structure of common sole stock that is the result of historical overfishing and the combined effect of high fishing pressure and low size selectivity [defined as the phenomenon of fishing effectiveness varying with the size of the fish (Beverton and Holt, 1957; Quinn and Deriso, 1999)] is well recognised. Actually, the catch composition of sole in the northern and central Adriatic Sea is dominated by ages 0 and 1-year specimens, with a low occurrence of large individuals (e.g. STECF, 2009). It is important to stress that the demographic erosion can increase the variability of sole-stock abundance due to the reduced ability of the population to successfully cope with environmental fluctuations (Anderson et al., 2008; Stenseth and Rouyer, 2008). Demographic erosion affects not only the spawning capacity of the stock but also the average market price and revenues from fishing activities.

The common sole stock in the northern and central Adriatic Sea has been considered and assessed inside a management unit defined by FAO-GFCM as Geographical Sub-Area 17 (Northern Adriatic Sea). Management units are commonly based on jurisdictional and management convenience instead of biological inference (Smedbol and Stephenson, 2001; Stephenson, 1999). Boundaries between stock management areas can often bisect subpopulations resulting in the inclusion of fish from a single sub-population in 2 separate stock assessments. However, tagging experiments using the traditional mark-and-recapture procedure showed that all of the soles caught in GSA 17 were recaptured in the sub-basin (Pagotto et al., 1979). Furthermore, the local currents, eddies, and geomorphological and oceanographic features of this sub-basin differ markedly from those of the southern Adriatic (FAO-GFCM GSA 18) and Ionian Sea (FAO-GFCM GSA 19; Artegiani et al., 1997) preventing high rates of exchange of adult spawners and mixing of planktonic larval stages from nursery areas in adjacent basins (Magoulas et al., 1996). Therefore, the hydro-geographical features of this semi-enclosed basin may support the overall pattern of differentiation observed for the Adriatic common sole. The Northern Adriatic Sea (GSA 17) has a high degree of geographical homogeneity, with a wide continental shelf and eutrophic shallow waters. In contrast, the Southern Adriatic (GSA 18) is characterised by narrow continental shelves and a marked, steep continental slope (1200 m deep). This deep canyon may represent a significant geographical barrier for *S. solea*. Genetic studies (Guarniero et al., 2002) of sole specimens from 5 different central Mediterranean areas suggested that 2 near-panmictic populations of common sole exist in the Adriatic Sea. One of these populations inhabits the entire GSA 17, while the other seems to be spread along the Albanian coast (southern Adriatic, GSA 18). Further analysis of the Adriatic populations showed a low, but significant, differentiation between GSA 17 and GSA 18 populations, with possible gene flow from the eastern coastal side of GSA 18 into GSA 17 (AdriaMed, 2012).

The isolation of the common sole stock in GSA 17 from that in GSA 18 results in ideal conditions for study of the stock's population dynamics and to develop local management strategies.

Nearly all of the management strategies currently adopted by Mediterranean countries are limited to the control of fishing capacity, fishing effort, and the application of technical measures, such as mesh size regulations, establishment of minimum landing sizes, and closures of areas (e.g. 3 nautical miles from the coast permanently banned to towed gears) and seasons (e.g. fishing stop of towed gears during summer months). However, such technical measures have been rarely supported by scientific evidence (Lleonart and Maynou, 2003). For instance, the adopted EC legal minimum landing size for sole in the Mediterranean (20 cm; EC reg. n. 1967/2006) is not consistent with biologically meaningful target sizes, such as the size at first maturity ($L_m = 25.8$; Fabi et al., 2009) or the size at which a cohort attains its maximum biomass ($L_{opt} = 31$ cm; Colloca et al., 2013). Moreover, in the areas and periods with relatively high concentrations of juveniles, fishing pressure is intense due to the high relative density of fishing capacity and collateral impacts of fishing (e.g. habitat degradation, bycatch; Grati et al., 2013). Before a possible reduction in fleet capacity that would lead to sustainable and optimal exploitation of the common sole, but also to a heavy negative socio-economic impact on local fishing industries, more appropriate management measures should be evaluated. Specific spatial–temporal management of *rapido* trawl effort can be used to reduce the fishing mortality of the juvenile portion of common sole stock. In such view, the early concerns of the GFCM regarding fleet overcapacity and fishing pressure in the inshore nursery areas which might necessitate closures have been priorities for discussion since the 1950s (Caddy, 1993a).

Quantitative analysis of spatial management options is complicated, as information on the spatial dynamics of fleets and stocks is often unavailable and effective spatial models are difficult to construct (Holland, 2003).

In the present paper, we synthesise available information on the spatial patterns of *rapido* trawl fishing efforts, from Vessel Monitoring System (VMS), and common sole stock distributions, from trawl surveys, during the recruitment process and the early phase of the spawning period occurring in fall–winter. The combination of fishery dependent and independent data is utilised in an analytical framework for quantitatively simulating spatio-temporal *rapido* trawling management options aiming at reducing the catch of juveniles and increasing the spawning capacity of the stock in the medium term. The outcomes of different management approaches will be discussed, including how shifting the selection-at-age curve toward the right (older ages), can result in sustainable exploitation of the stock.

2. Materials and methods

2.1. Study area and trawl survey data

Stock distribution data were obtained from *rapido* trawl surveys (SoleMon) carried out in a 36,742-km^2 area of the northern and central Adriatic Sea up to 100 m depth, from the Italian coast to 12 and 6 nautical miles from the Croatian and Slovenian coasts, respectively (Fig. 1). The surveys were conducted in fall from 2005 to 2011 by the National Research Council (CNR-ISMAR UOS Ancona, Italy) in cooperation with the Institute for Environmental Protection and Research (ISPRA, Italy), the Institute of Oceanography and Fisheries (IOF, Croatia), and the Fisheries Research Institute of Slovenia (FRIS, Slovenia).

A systematic sampling strategy was adopted during the first exploratory survey (2005). Based on the data collected during the first year, the haul positions were randomly distributed in three depth strata, identified as 0–30 m (36 stations, 11,361 km^2), 30–50 m (19 stations, 8410 km^2), and 50–100 m (11 stations, 16,971) and then sampled in the following years following a fixed-station design. Sixty-six stations were sampled each year from 2007 to 2011 with the exception of 2006 when, due to technical constraints, it was possible to sample only at 56 stations (Table 1; Fig. 1).

In the present study, we excluded 2005 survey data as the sampling strategy in that year differed from that used in 2006–2011. Sample data from 2006 to 2011 were pooled. We also excluded data from hauls carried out inside Slovenian (one haul each year) and Croatian waters (11 hauls, only in 2006), respectively because they occurred in different zones and only for 1 year.

Haul duration ranged from 4 to 46 min, depending on the seabed texture. However, each year more than 95% of the hauls had a duration of 30 min. The towing speed was 5.5 knots. *Rapido* trawls were provided with DST Logic Temperature and Depth Recorders. The use of these devices and the fixed size of the gear mouth provided the exact location of the area swept by each *rapido* trawl. An exhaustive description of the survey strategy and sampling procedure is reported in (Grati et al. 2013) and in the SoleMon sampling protocol (SoleMon, 2012).

All soles in the catches were measured (total length; mm) and weighed (wet weight; g). Sex and maturity stage of gonads were assessed basing on the classification described by Holden and Raitt (1974). Otoliths were collected from a subsample of specimens from each haul every 0.5 cm of total length for each sex. The absolute number of soles and otoliths sampled is presented in Table 2. The whole sagittae were read by 2 expert readers using the protocol described in TACADAR (2006).

Density (number of individuals km^{-2}) was calculated for each age class (0, 1, 2, 3, 4, 5+ years) and each haul (Grati et al., 2013). Age density data for 2006–2011 were pooled to maximise the information available for the autumn stock recruitment and spawning period. These data were included in the following geostatistical analyses.

2.2. Estimating common sole hot spot distribution by age

The same geostatistical approach employed by (Grati et al. 2013) was used to analyse spatial variograms of the density abundances of each age class of sole. Ordinary Kriging algorithms were applied to interpolate the data for each age, based on the parameters obtained from variogram analyses using a 5-km grid.

To identify areas that contained high densities of sole of each age, we built a geostatistical aggregation curve for the estimated spatial distributions. Geostatistical aggregation curves were originally defined by Matheron (1981), and subsequently elaborated by Petitgas (2009), to describe changes in spatial distribution as a function of variations in population abundance. A geostatistical aggregation curve relates the relative abundance of individuals P(y) to the area T(y) occupied by those individuals for densities greater than y. To calculate the aggregation curve, all 5-km cells were ranked according to their density from maximum to minimum. Along this gradient, we calculated for each cell the cumulative abundance as a proportion of the total abundance, P(y), and the proportion of the total area, T(y). Both P(y) and T(y) range from 0 to 1, and the resulting curve describes the cumulative abundance with increasing area. P(y) and T(y) can be formalised mathematically as:

$$P(y) = \sum_{i=1}^{k} \frac{n_i}{N} \tag{1}$$

$$T(y) = \sum_{i=1}^{k} \frac{a_i}{A} \tag{2}$$

where n_i is the number of fish in density class i, a_i is the area occupied by those fish for each class i and N is the total number of fish in the total area, A. We calculated a relative geostatistical aggregation curve P(T) for estimated spatial distribution by combining Eqs. (1) and (2). For each geostatistical aggregation curve of each age, we identified the location where a line that was tangential to the curve had a 45° slope. Each curve up to the 45° tangent point included a specific percentage of cells. This percentage was used to find the corresponding percentile of the estimated fish density distribution and, thus, the high density patch threshold for each age group (Colloca et al., 2009).

The geometrical properties of the 45° tangent to the relative aggregation curve correspond to a change in the spatial distribution of fish from a dispersed distribution pattern to an aggregated pattern. For fish densities lower than the above-identified threshold, a relative increase in the area is followed by a proportionally lower increase in the number of fish included. Conversely, above the threshold, the relative increase in the number of fish is higher than the increase in area.

2.3. Rapido trawl fleet and estimation of spatial distribution effort with VMS data

In this study, VMS data for the activity of 100 vessels in the Italian fleets operating in the northern and central Adriatic Sea were used to quantify the pattern of *rapido* fishing effort in the fall periods (October–December) of 2006–2011. These 100 vessels represented almost 95% of the entire *rapido* trawl fleet, which is characterised by a mean overall length of 24 ± 2.7 m and a mean gross tonnage of 66.3 ± 28.7 t (Fabi et al., 2009). The *rapido* trawl vessels usually operate with four gears simultaneously, for 18–22 h per day and 4–5 days per week all year round, with the exception of 45–60 days in the summer during the biological stop for trawling activities. Most of the vessels are located in Chioggia Harbour (45), followed by Ancona (13) and Rimini (12; Fabi et al., 2009).

In Slovenia *rapido* trawl is not utilised, while in Croatia, according to the Fishing acts (Narodne novine, 148/2010, 25/2011), the *rapido* trawl is only employed for catching shellfish, and the rate of other species in the catches cannot exceed 20% by weight.

VMS signals were processed following the rationale proposed by Bastardie et al. (2010) and the methodological procedures described by Russo et al. (2011a, 2011b, 2013). Briefly, fishing tracks (fishing trips starting from, and ending in, a given harbour) which were natively characterised by a low frequency (2 h between successive pings) were interpolated at a standard frequency of 10 min between successive pings (Russo et al., 2011a). These high-frequency tracks were then inspected to distinguish fishing from steaming points by using a speed filter (fishing points were associated with a speed range of 5–7 knots, the usual speed of *rapido* trawling operations; Fabi et al., 2009). Such approach is widely used and has been validated for towed gears (Lambert et al., 2012; Piet et al., 2007). Finally, all of the fishing points for the autumnal months of each year were plotted over a grid with 5 km × 5 km squares. The resultant grid cells were used as input in further analyses, indicating the total number of fishing pings in each cell. Fishing units (vessels) were not individually identified, but were grouped in fleets by harbour.

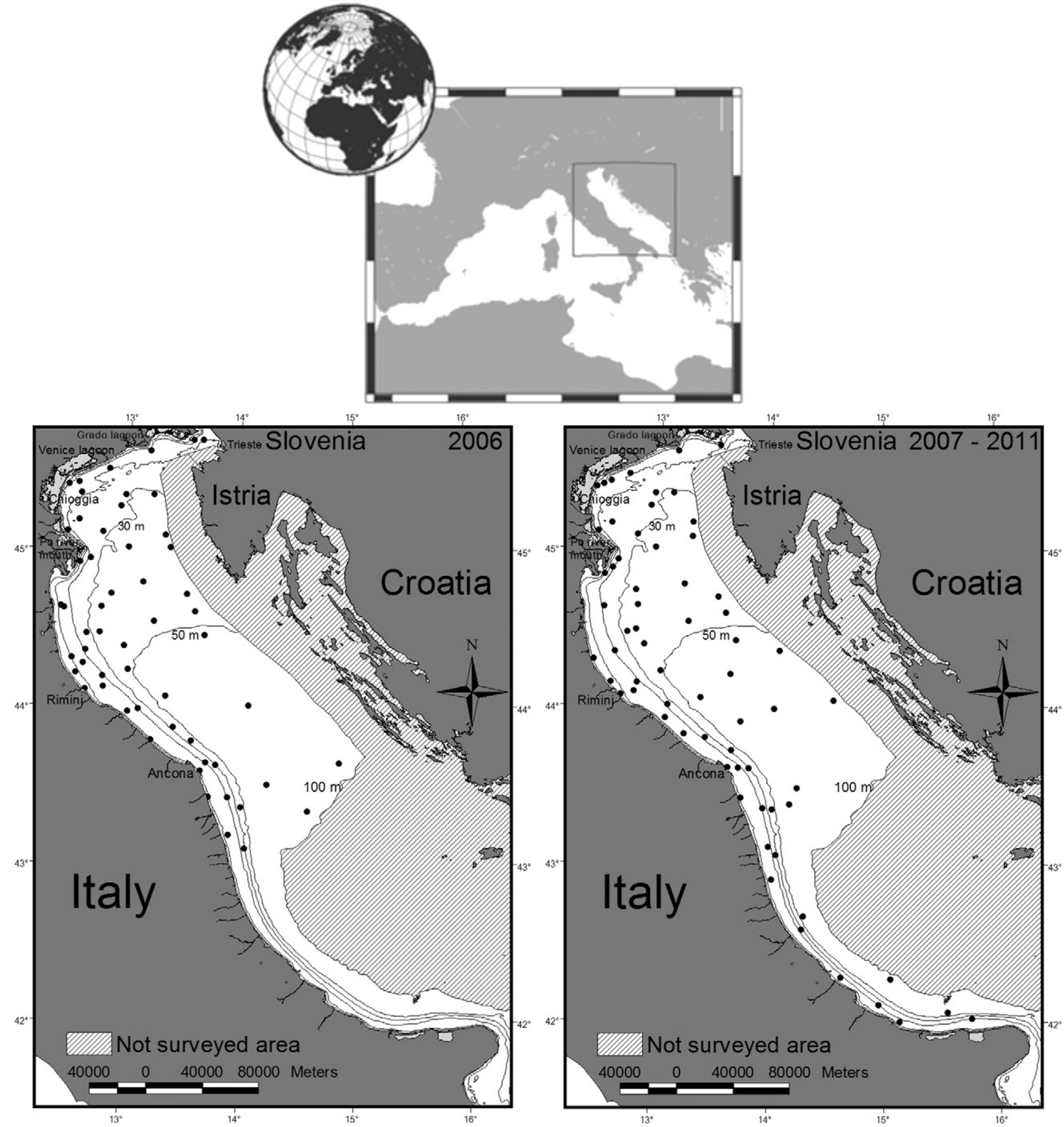

Fig. 1. Map of study area with the locations of the hauls conducted and used in the analysis.

Table 1
Sampling period, depth, temperature, tow duration and swept area. SD = standard deviation.

Year	Date		N. of stations sampled			Depth(m)			Temperature (°C)			Tow duration (min)			Swept area (km^2)		
	Start	End	S1	S2	S3	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD
2006	26/10/2006	10/11/2006	32	15	9	8.2	93.1	32.3 ± 18.4	12.0	16.0	14.7 ± 2.1	5	44	25.9 ± 9.1	0.018	0.142	0.064 ± 0.022
2007	30/11/2007	22/02/2008	36	19	11	11.4	93.3	33.8 ± 20.3	13.7	17.5	16.4 ± 1.1	5	46	30.6 ± 9.2	0.011	0.093	0.052 ± 0.026
2008	20/10/2008	22/02/2009	36	19	11	8.5	93.4	31.6 ± 20.4	12.7	19.5	16.3 ± 2.2	5	36	26.3 ± 7.5	0.006	0.041	0.033 ± 0.008
2009	18/11/2009	17/12/2009	36	19	11	8.3	89.9	28.8 ± 17.3	13.5	18.7	15.8 ± 1.5	4	45	25.1 ± 8.8	0.008	0.050	0.023 ± 0.008
2010	04/11/2010	18/11/2010	36	19	11	8.4	92.1	31.3 ± 18.6	14.2	17.8	16.3 ± 1.2	5	35	25.7 ± 8.7	0.011	0.041	0.029 ± 0.009
2011	14/11/2011	28/11/2011	36	19	11	8	93	32.1 ± 20.3	13.8	17.6	15.6 ± 1.3	5	39	27.7 ± 7.5	0.013	0.047	0.033 ± 0.009

Table 2
Number of *S. solea* and otolith sampled subdivided by sex. ND = sex not determined.

Year		N. of soles sampled			N. of sole otolith sampled	
	Total	Males	Females	ND	Males	Females
2006	1665	795	795	75	163	185
2007	2103	511	617	975	146	128
2008	788	376	408	4	115	108
2009	941	471	470	–	125	136
2010	1077	541	535	1	154	168
2011	1660	780	876	4	164	174

2.4. Estimation of rapido trawl population-selection curve

The approach described by Sampson and Scott (2011) was used to estimate the population-selection curve of the *rapido* trawl fishery. Sampson and Scott (2011) implemented a model for population-selectivity with 4 main parameters: a set of regional fishing mortality coefficients, the spatial distribution of recruits, a set of spatial movement coefficients, and a curve for gear selection. The first 2 sets of parameters were estimated by using 5 km^2 grid-cell data of high density patches of sole recruits (Age 0 group) and *rapido* trawl fishing effort. The spatial movement coefficients were extrapolated from a mark–recapture study by Pagotto and Piccinetti (1982) and the gear-selection curve was extrapolated from a selectivity study carried out by Ferretti and Froglia (1975).

To explore the role of the population-selection curve in fish population dynamics, we considered the population to be partitioned into distinct subpopulations occupying discrete spatial regions and assumed limited exchange of fish between regions. The fish within each region all suffer from the same instantaneous rate of age-specific natural mortality (Scarcella et al., 2012), but they potentially experience different instantaneous rates of age-specific fishing mortality. In this formulation, the gear-selection curve is the same across all regions, but fish in each region may suffer different absolute levels of fishing mortality. Using equation 4 from Sampson and Scott (2011) the possible shapes of population-selection curves were derived based on 3 regions, 6 age classes, a natural mortality vector (Scarcella et al., 2012), and a logistic gear-selection curve (with age_{50} = 1.4 and b = 0.5; Ferretti and Froglia, 1975). Three regions were selected within GSA 17, from the Italian coast to a depth of less than 100 m subdivided as follows:

- Region 1: 0 to 6 nautical miles from the Italian coast.
- Region 2: 6.01 to 9 nautical miles from the Italian coast.
- Region 3: 9.01 nautical miles from the Italian coast to the edge of Slovenian and Croatian territorial waters (6 or 12 nautical miles from their respective coasts).

In each region, the recruits were partitioned based on the high density patch estimates of the previous calculations. These values and the proportions of fishing effort estimated from VMS data in each region were used as input data to calculate the population selection curve for the *rapido* trawl fishery.

The movement coefficients were considered as an asymmetric dispersion from region 1 toward regions 2 and 3, following the information reported by Pagotto and Piccinetti (1982). Three different rates of dispersion (0.2% $month^{-1}$; 0.1% $month^{-1}$; 0.05% $month^{-1}$) were tested.

Map representations of both sole high density patches by age and *rapido* trawl effort were created by using Manifold® System. The same software was utilised to estimate high density patch surfaces for each age class and *rapido* trawl effort in each region defined before.

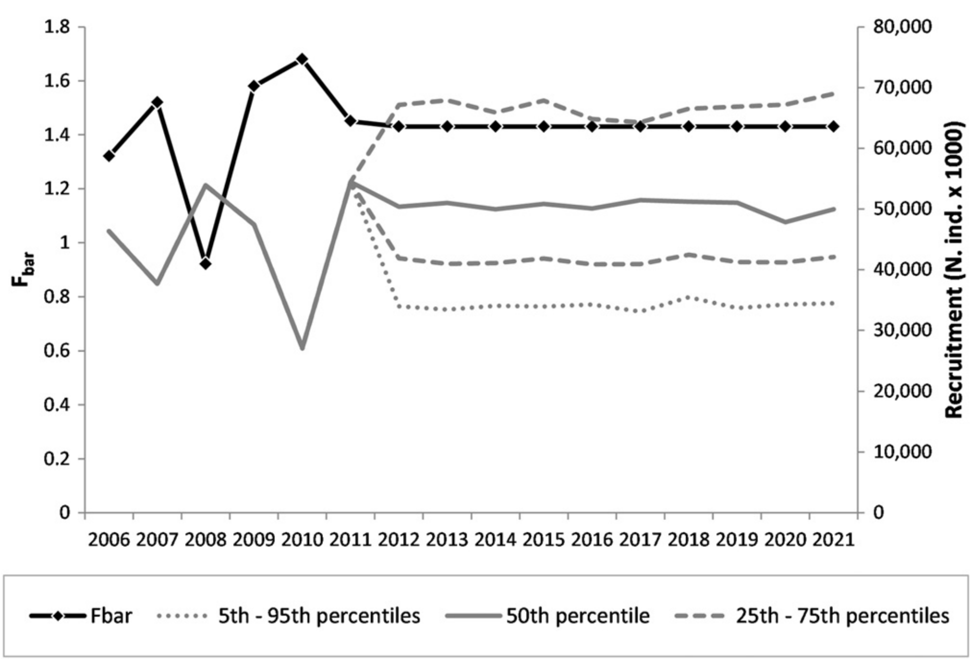

Fig. 2. Fishing mortality and recruitment employed in the forecasts.

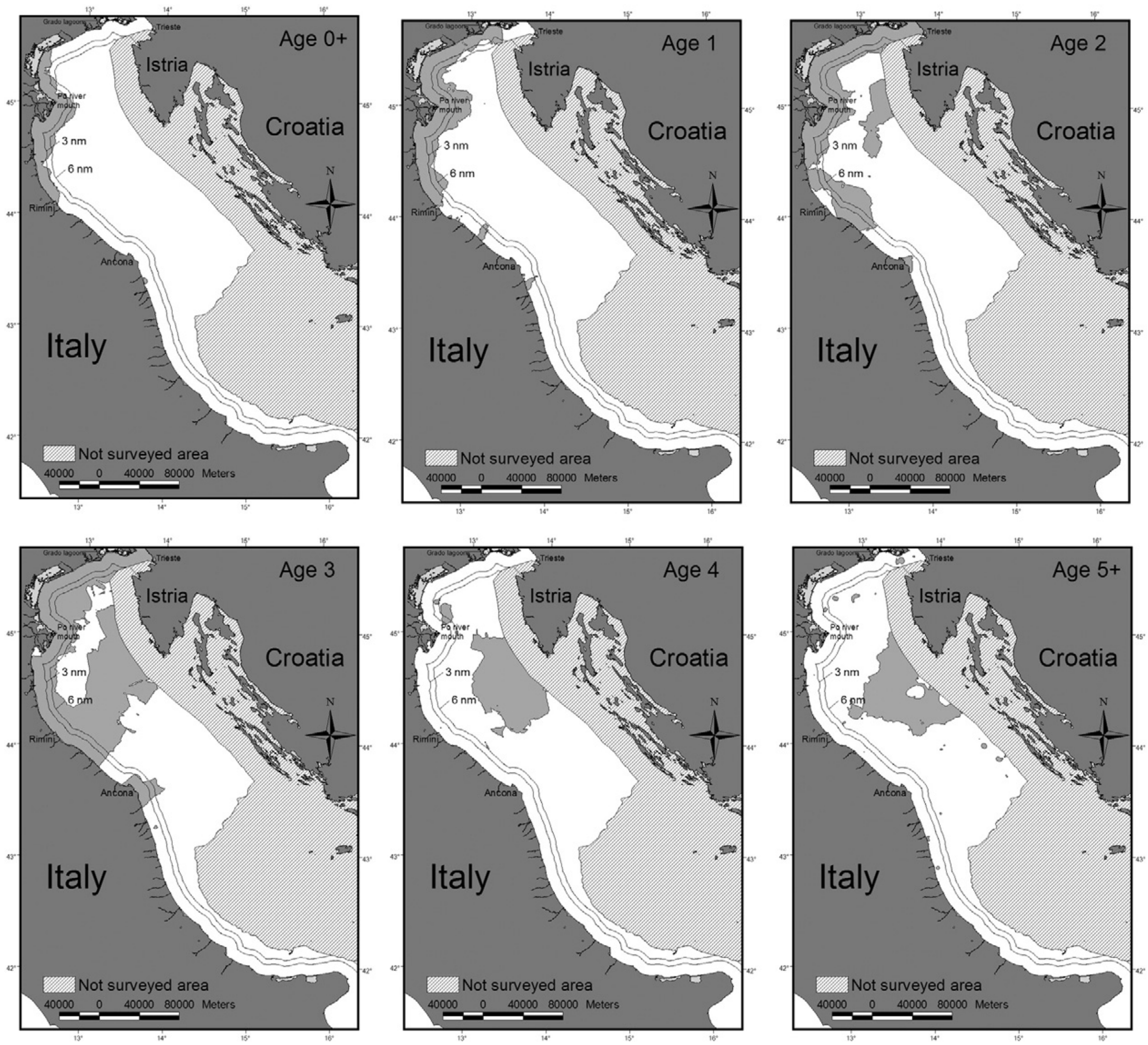

Fig. 3. Maps of hotspots calculated for the age classes of soles.

2.5. Spatial management scenarios

Using the approach described by Sampson and Scott (2011), the shape of the population-selection curve was changed basing on the following 2 scenarios:

- Scenario 1: Ban of *rapido* trawling within 6 nautical miles of the Italian coast from October to December.
- Scenario 2: Ban of *rapido* trawling within 9 nautical miles of the Italian coast from October to December.

For each of these proposed scenarios, we assumed that when the *rapido* trawl fishery is banned in region 1 (scenario 1) and in regions 1 and 2 (scenario 2), the fishing mortality is redistributed to region 3, proportionally with the information derived from the VMS data.

2.6. Forecast of the stock for each scenario

Projections from 2012 to 2021 were implemented by using the NOAA Fisheries Toolbox AGEPRO 3.4.1 (Brodziak et al., 1998). This model represents an iteroparous fish population with changes in abundance due to fluctuations in recruitment, natural mortality, and fishing mortality.

Forecasts assumed a constant fishing mortality after 2012 that was the average F_{bar} (1.4) from 2006 to 2011, as reported in the most recent stock assessment by the FAO-GFCM WG on Demersal Stocks (Scarcella et al., 2012). Similarly, recruitment values from 2012 to 2021 were derived from the geometric mean of the recruitment over the observed range (2006–2011) in the FAO-GFCM WG stock assessment (Fig. 2). The maturity ogive, natural mortality vector, number of individuals and weight-at-age for stock and for catch were derived from the same source (Scarcella et al., 2012).

Fishery age-selectivity for each gear that targeted sole in GSA 17 was included in the AGEPRO 3.4.1 model. The exploitation pattern for the forecasts remained unchanged for set nets and otter trawls, but was proportionally modified for *rapido* trawls. The selectivity curves that resulted from the previous analyses were used for the status quo and the 2 proposed scenarios for each of the 3 dispersion rates tested.

In each forecast run, 500 simulations were included, to project using stochastic recruitment. In each simulation, recruitment was multiplied by log-normally distributed noise, which had a mean of 1 and a standard deviation of 0.3 (Fig. 2).

Primary outputs of the model include the projected spawning biomass and landings by period (only median values are presented).

3. Results

3.1. Spatial distribution of sole by age

The geographical distribution of common sole high density patches in fall differed with age class (Fig. 3). Age 0 and 1, represented mainly by immature fish and mean TL respectively of 16.3 ± 1.3 and 20.3 ± 0.8 cm, were distributed in inshore Italian waters from Rimini to Grado Lagoon. Of all soles aged 0 and 1, 90% and 60% respectively were distributed in region 1. The age 2 high density patches were represented by 45% of mature and 55% by immature fish and had a mean TL of 23.8 ± 0.8 cm. They were distributed in regions 1 (45%), 2 (18%), and 3 (37%). Almost 70% of age 3 soles consisted of mature specimens having mean TL of 26.6 ± 1.7; they were found in region 1 from Ancona to Trieste Gulf (31%), in region 2 (12%) and in region 3 (56%), especially in the far east of the study area, toward the Istria peninsula. The age groups 4 and 5+ were represented almost entirely by mature specimens and mean TL were respectively 28.7 ± 2.3 and 32.5 ± 2.8 cm. A few high density patches for ages 4 and 5+ were found inshore north of the Po River mouth, but the most high density patches (98% and 97%, respectively) occurred offshore within region 3.

3.2. Spatial distribution of rapido trawl fishing effort

Fig. 4 shows the fall *rapido*-trawl effort of Italian vessels over the years 2006–2011 concentrating mainly in 3 main fishing grounds. The first was the inshore zone between 3 and 9 nautical miles from the Italian coast, between 43° and 44° latitude, that was mainly exploited by the vessels belonging to Ancona and Rimini harbours. The second zone was located between Po river mouth and Venice lagoon at the same distance from the coast as the first region. The Chioggia rapido trawl fleet mainly exploited this region. The third area of effort concentration was offshore, near Istria peninsula and was exploited by both Chioggia and Rimini *rapido* trawl fleets. As expected, the area characterised by low abundance of sole has a relatively low fishing effort. Forty-five per cent of the fishing effort was concentrated in region 1, 25% in region 2, and 30% in region 3.

3.3. Changes in selectivity of rapido trawl fishery and projections

The population-selective curves, assuming an asymmetric dispersion rate of 0.05% per month, are shown in Fig. 5a, together with the asymptotic gear-selection curve as predicted by Ferretti and Froglia (1975). The *status quo* scenario had a dome-shaped pattern with high selectivity for ages 0 and 1-year, due to the high abundance of recruits in region 1 and the high concentration of fishing effort in that region. Scenarios 1 and 2 as banning rapido trawl fishing in region 1 and regions 1 and 2 respectively, would result in a decrease in selectivity for young soles.

With higher dispersion rates (Fig. 5b and c) the status quo population-selection curve is similar to the asymptotic gear-selection curve. In both cases, the 2 proposed scenarios resulted in a clear decrease of selectivity for the young age classes and a sharp increase in selectivity for older age classes.

The projections of the SSB and landings for the status quo and for scenarios 1 and 2 are presented in Fig. 6. These projections assume the fishing mortality and recruitment presented in Fig. 2 and the selectivity curves for *rapido* trawl shown in Fig. 5. The population-selective curves derived from different rates of asymmetric dispersion predicted a reduction in both SSB and landings over a 10-year period. In contrast, forecasts using management scenarios 1 and 2 predicted an increase in SSB and landings over the same period. The highest rate of dispersion resulted in the largest SSB and landing predictions, as individuals dispersed quickly to areas with relatively low fishing effort.

4. Discussion

This paper is, to our knowledge, the first one using a quantitative approach to demonstrate how straightforward spatial management measures could result in a clear increase of the spawning potential of the stock and consequently of landings and revenues for the fishery. In the present paper we provide an accurate outline of the spatial distribution by age of the sole in the northern and central Adriatic Sea as well as the spatial pattern of fishing effort of the main gear exploiting the resource. The spatial distributions by age clearly showed a segregation between age groups 0–2, characterized mostly by sexually immature specimens,

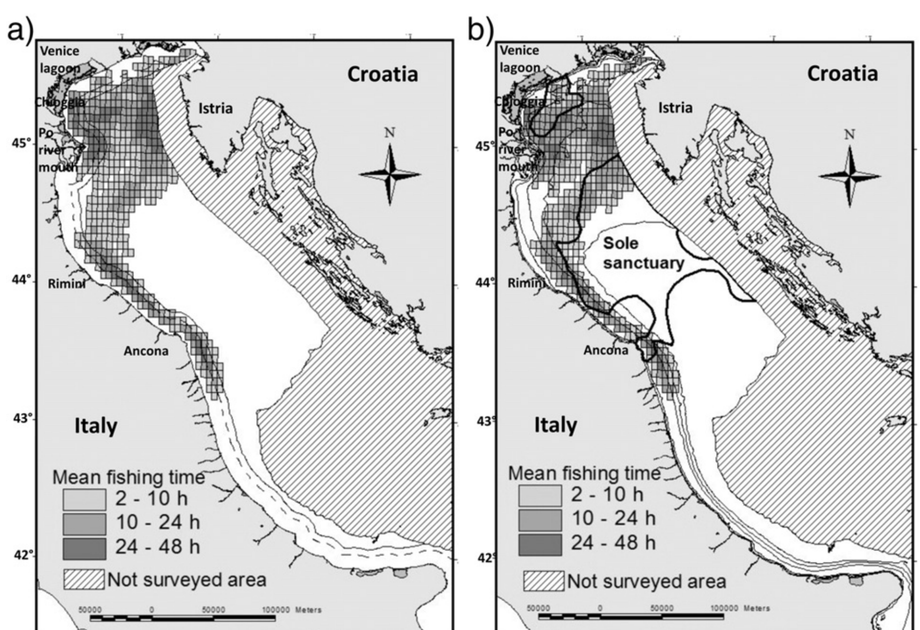

Fig. 4. Maps of spatial distribution of *rapido* trawl fishing effort estimated in mean hour of fishing in each 5 × 5 km rectangle. In map (a) the 6 and 9 nautical miles from the Italian coast are shown respectively by broken and continuous black lines. In map (b) the bathymetry is shown with continuous grey lines and temporal persistency (>75%) of the estimated areas where adults of soles are concentrated is shown by black bold line from Grati et al., 2013.

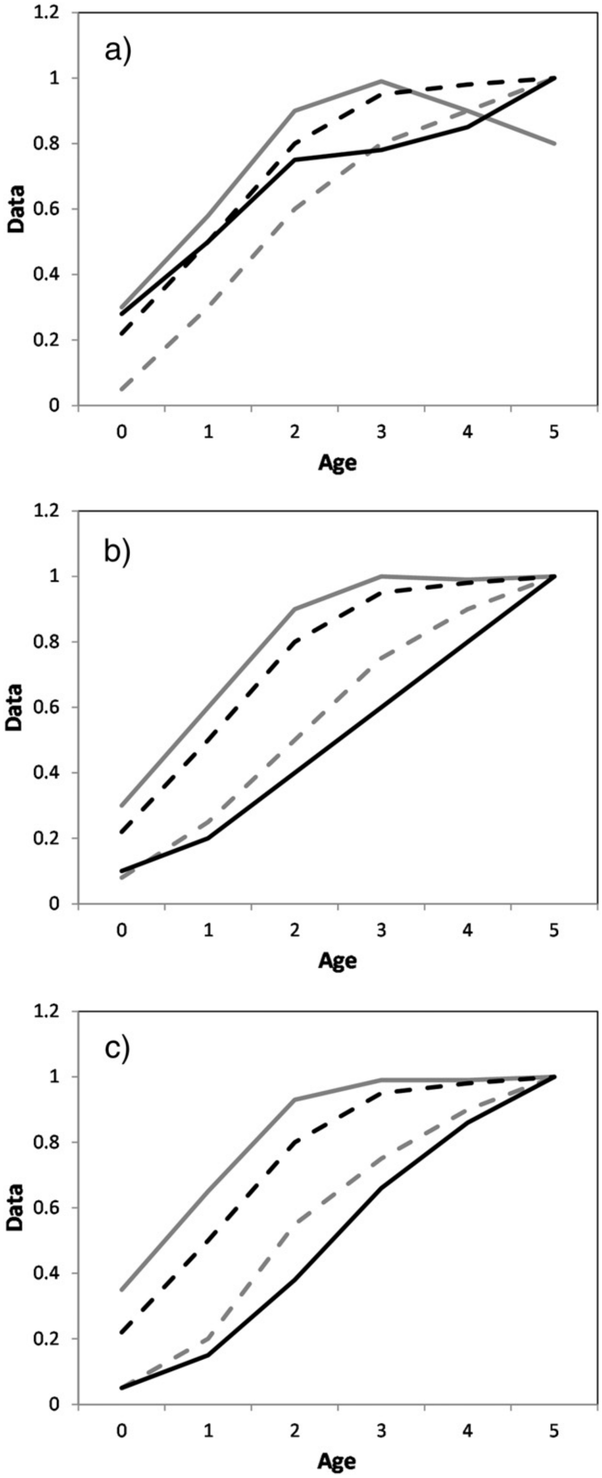

Fig. 5. Population-selection curves generated by the three-region model with differing instantaneous rates of fishing mortality in each region. In panel (a), there is an asymmetric dispersion with a rate of 0.05% month^{-1}. In panel (b), there is an asymmetric dispersion with a rate of 0.1% month^{-1}. In panel (c), there is an asymmetric dispersion with a rate of 0.2% month^{-1}. All cases have the same asymptotic gear-selection curve, shown by the broken black line. The status quo scenario is shown by continuous grey line. The scenarios 1 and 2 are shown respectively by the continuous black line and the broken grey line.

and 4–5 +, generally mature fish, with a clear enlargement of high density patches until age 3 followed by a shrinkage observed for ages 4 and 5 +, confirming the outcomes observed by Piccinetti and Giovanardi (1984) and (Grati et al. 2013). Taking into account the relationship between spatial distribution of *rapido* trawl fishing effort and common sole by age it is possible to ascertain that *rapido* trawl activity focuses in areas of high concentration of juvenile soles of ages from 0 to 2, determining consequently negative trend in the spawing stock biomass (Scarcella et al., 2012).

The spatial simulations carried out in the present study respond to a need for complementary methods for the management of fisheries (Botsford et al., 1997; Christensen and Maclean, 2011; Link, 2011; Walters and Martell, 2004). The potential benefit of area closures depends on assumptions about the spatial concentration of juveniles, dispersion rates, and concentration of fishing effort. However, the results are qualitatively robust to the suite of assumptions included in the sensitivity analysis conducted in which different rates of dispersion were considered.

The simulation of two management scenarios showed that a change in selectivity would lead in all cases to a clear increase in the SSB and an increase in landings of sole in the medium-term. The *rapido* trawl activity currently targeting sole stock in the northern and central Adriatic Sea can be conducted by using a different rationale, considering that catches and incomes could increase with small changes in the spatial pattern of the *rapido* trawl fishing effort.

The common sole stock is not yet depleted and faces a situation of growth overfishing, in spite of the high level of fishing mortality observed since 2006. This is likely due to the reported higher resilience of Mediterranean stocks as compared to Atlantic stocks (Lleonart, 2005). Such resilience is argued to be linked to high exploitation of juveniles but low adult mortality because of offshore spawning refuges, which can reduce the risk of stock depletion and collapse (Caddy, 1993b, 1999). In the case of common sole in northern and central Adriatic Sea, every year, a certain amount of spawners, inhabiting particular areas where it is difficult to operate with *rapido* trawls, manage to survive and produce a consistent amount of larvae. Indeed, a comparison of persistent spawning areas presented in (Grati et al. 2013) with the spatial distribution of the *rapido* trawl fishing effort (Fig. 4) indicates only partial overlap, mainly due to the difficulties operating *rapido* trawlers in areas that can be considered to be 'sole sanctuaries' (Fig. 4). These areas are characterised by high concentrations of debris and benthic communities that are dominated by holothurians (Despalatović et al., 2009). The difficulty in trawling using *rapido* inside 'sole sanctuaries', prevents the redistribution of *rapido* trawl effort to the off-shore region after implementation of the 2 proposed scenarios from resulting in a substantial increase in adult catch. In addition, the high density of off-shore gas platforms in the area creates permanent no-take zones and protects fisheries resources (Fabi et al., 2004; Scarcella et al., 2011). However, the effects of this exploitation regime on fisheries yield and the size-structure of exploited populations were poorly investigated, and the impact on the economy of fisheries not fully understood. Nevertheless, it is clear that improving the selection pattern of fishing gear or trawl gear would result in improved economic yields from demersal resources (Lleonart et al., 2003; Merino et al., 2008).

In the Adriatic Sea, the Italian government in agreement with the European legislation (EC reg. n. 1967/2006) has adopted a series of management measures to facilitate the recovery of marine resources and to rebuild ecosystems. These measures include: (i) freezing the number of fishing licences, (ii) declaring closed fishing seasons, (iii) implementing seasonal spatial and temporal trawl closures, (iv) banning harmful fishing gear (e.g. drifting gillnets since 2003), and (v) protecting juveniles (minimum sizes for several target species; AdriaMed, 2005). Additional management measures include technical regulations (mesh size and fishing gear) and stock-rebuilding projects (protected areas and fishing zones). Of these measures, 2 sets are of particular interest. The first set includes spatial and temporal closures applied to all or selected gear types. These measures cover permanent spatial closures to specific trawl (also *rapido* trawl) and seine gear types. For example, the use of trawls, seines, or similar nets are prohibited within 3 nautical miles of the coast or within the 50 m

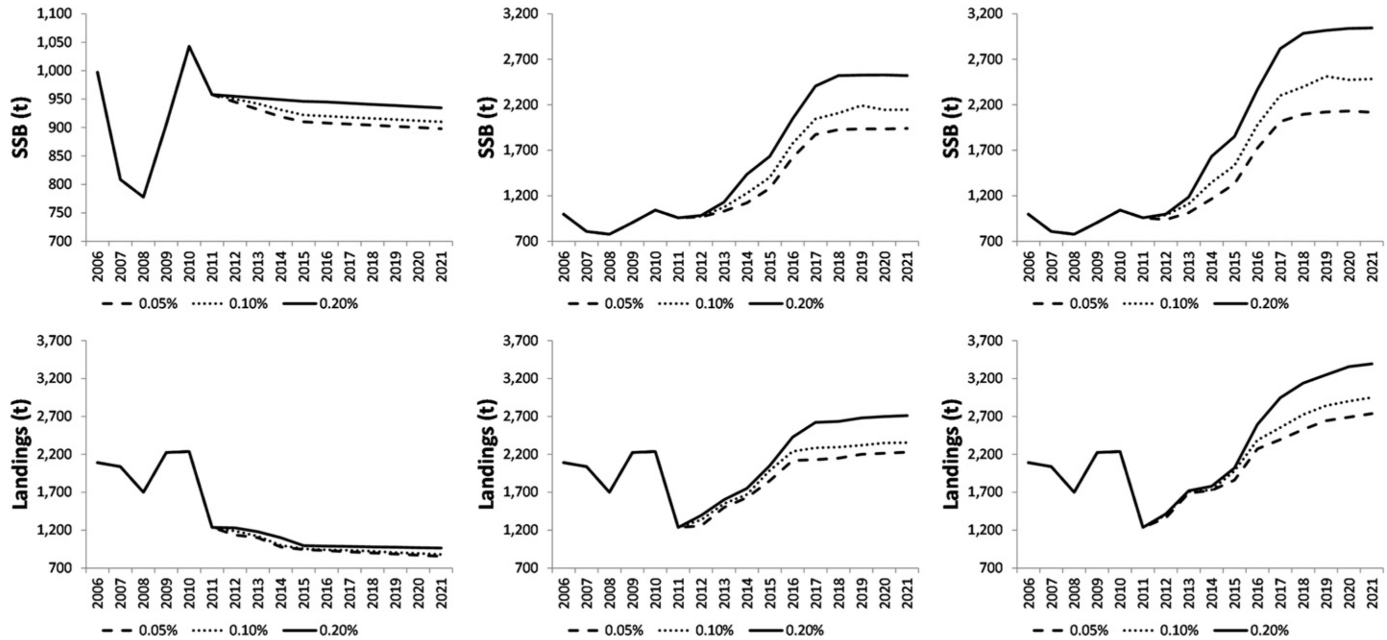

Fig. 6. Trends of spawning stock biomass (SSB) and landings for the status quo scenario, scenario 1 and scenario 2 considering the three rates of dispersion.

isobath, where this is closer to the coast. Temporal closures regard bottom and mid-water trawl nets during summer for 30–45 days (AdriaMed, 2005; Demestre et al., 2008). A second set of measures incorporate the establishment of marine protected areas. In the northern and central Adriatic Sea, there are currently 2 marine protected areas (Miramare and Tremiti), 4 biological conservation zones (areas of Tenue, Tegnue di Porto Falconera, Fuori Ravenna and the gas extraction field Barbare; Fouzai et al., 2012) and a SIC area as a '*Paguro*' platform. The proposed scenarios involving temporary closures of coastal areas could work in synergy with these management programmes.

The decrease of fishing mortality, as advised in both FAO-GFCM and EC-STECF reports (e.g.: STECF, 2009; Scarcella et al., 2012), requires actions by the management sector, which must implement policies aimed at containing fishing, restricting catches, and protecting the marine environment. The management policy in force in the Mediterranean Sea is based primarily on the control of fishing effort, which is the major cause of depleted fish stocks. The situation is usually aggravated by damage to marine ecosystems, as in the case of the northern and central Adriatic Sea. Unfortunately, reductions in fishing effort, in terms of both fishing days and fishing gear-units, lead to discontent among fishermen and usually intensify disagreements between individuals engaged in different fishing activities, such as those between trawlers and artisanal fishermen. Moreover, management objectives based on controlling fishing efforts, are problematic, in that increases in efficiency cause increases in effective effort, even when the apparent effort remains the same. The gradual increase in the efficiency of fishing methods and gears is sometimes referred to as 'technology creep'.

Furthermore, only few cases have shown reduction in fishing effort that has helped to rebuild depleted marine fish populations and ecosystems (Lotze et al., 2011; Worm et al., 2009). This has been achieved by merging diverse management actions, including effort restrictions, gear modification, and closed areas.

This study evaluated existing spatial management regimes and potential new spatial and temporal closures in the northern and central Adriatic Sea using a simple modelling tool. The simulations carried out following the 2 scenarios of closures produce results similar to those proposed by Scarcella et al. (2012), where global reduction of fishing mortality was proposed. However, the simulations in the current study differ from those of Scarcella et al. (2012), in that the spatial simulation does not impose a reduction in the number of fishing days at sea, the number of vessels in the fleet, or the establishment of fish quota. The focus of the simulation is that the effort of the *rapido* trawl is moved far from the coast during key sole recruitment periods, when the juveniles are moving from the inshore nursery area toward the feeding areas. Moreover, considering the multispecies catches of *rapido* trawl fishery, this measure will surely have a positive impact also for the juveniles of other demersal species that aggregate in coastal areas during summer–fall (i.e.: *Mullus barbatus*, *Chelidonichthys lucernus*, *Penaeus kerathurus*). The positive effect of moving the *rapido* trawl impact in deeper waters is represented by the decrease of discarded portion, both in terms of species without any commercial value and specimens below the minimum landing size (Scarcella et al., 2012).

Certainly, increased knowledge of stock connectivity (Volckaert, 2013), the stock-recruitment process, the spatial distribution of the resource and *rapido* trawl effort throughout the year, and other fisheries, as well as the artisanal fishing fleet exploiting sole with set nets, will lead to a more sophisticated and accurate model to be used by the management sector.

The 2 proposed management scenarios may also decrease conflict between *rapido* trawlers and gillnetters. In the last quarter of the year, *rapido* trawlers, as shown in Fig. 4, exploit the area between 3 and 6 nautical miles off the coast, where they fish juveniles that are moving to deeper waters. The occurrence of illegal trawling within 3 nautical miles of the coast and the reduction of fishing ground available for artisanal fishermen creates conflicts between the 2 sectors. The development of mariculture in coastal areas and other human activities (e.g. recreational fishery) has dramatically reduced the area available for setting gear. To test new fishing grounds, gillnetters often operate with their set gears farther than 3 nautical miles off shore, where there is a risk of damage to their gear due to trawler activity. The closure of the *rapido* trawl fishery within 6 or 9 nautical miles of the coast could resolve such conflicts. If trawling activity is moved further offshore, the unsustainable increase in the set net catch would be quite unlikely, because gillnetters have been already employing the maximum allowed length of nets (5000 m, EC reg. n. 1967/2006) since the beginning of this decade (Fabi et al., 2002). Furthermore, artisanal fishery efforts will move further offshore, producing a change in selectivity toward the older age classes, likely leading to results similar to those of the 2 *rapido* trawl fishery closure scenarios. The chance of increasing set net effort in the sole refuge area is quite unlikely, considering the technical features of artisanal fleets, which are characterised by smaller vessels with limited engine power, and the risk of conflicts with otter trawlers that usually operate in the refuge area.

Certainly the practice of illegal trawling carried out inside the 3 nautical miles is well acknowledged in the area. As a matter of fact, in the last decade the deployment of ad-hoc anti-trawling artificial structures specifically at 3 nautical miles of distance from the shore determined a decrease of this illegal activity. However the same malpractice could occur at 6 and 9 nautical miles, and due to the not permanent feature of the proposed measures other actions, as enhance monitoring, control and surveillance, or procedures aiming at a temporary disqualification of fishing licence, could address the problem of illegal trawling in those areas.

From a cost–benefit perspective, a more complex spatial management may also impose additional administration costs. Assuring compliance with area closures can be costly if enforcement at sea is required. These costs may be considerably lower if vessel monitoring systems are required. Effective use of area closures, particularly in multispecies fisheries, also requires large amounts of information about spatial dynamics. The surveys and port sampling programmes that generate data for current stock assessment are not designed to provide information about spatial heterogeneity within, or across, fish stocks. Collecting this information will be costly and the possible benefits of area closures must be balanced against these increased costs (Holland, 2003). Moreover, it is important to consider safety costs. Requiring *rapido* trawl vessels to fish far from the coast during a season that is often characterised by sub-optimal weather conditions may require improvement in coast guard rescue efficiency. Such costs are difficult to calculate. Cost–benefit analysis of spatial fisheries management is therefore not straightforward, but given the increase in projected fishing yields and the increase in the mean price of landings, it is likely that the proposed scenarios will have a positive influence in the view of sustainable management of the sole stock in the northern and central Adriatic Sea.

In conclusion, with increasing use of the marine environment, spatial aspects of marine management are becoming increasingly important, and include conservation issues that are becoming an integral part of overall spatial planning (Mackelworth, 2012). The ecosystem approach to fisheries management should be implemented in conjunction with spatial planning, given the spatial heterogeneity of fish populations (Eero et al., 2012). The northern and central Adriatic Sea can be considered a study case for consideration of biological interactions when developing new fisheries management measures. The present study contributes to this process by highlighting the importance of taking into account spatial dimensions of fishing fleets and the possible interactions that can occur between fleets and target species, facilitating the development of control measures to achieve a healthy balance between stock exploitation and socio-economic factors.

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