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Spatial assessment of fishing effort around European marine reserves: Implications for successful fisheries management

Vanessa Stelzenmüller [a,g,*], Francesc Maynou [a], Guillaume Bernard [e], Gwenaël Cadiou [e], Matthew Camilleri [c], Romain Crec'hriou [b], Géraldine Criquet [b], Mark Dimech [c], Oscar Esparza [d], Ruth Higgins [f], Philippe Lenfant [b], Ángel Pérez-Ruzafa [d]

[a] Institut de Ciències del Mar (ICM-CSIC), Passeig Marítim de la Barceloneta, 37-49, 08003 Barcelona, Spain
[b] UMR 5244 CNRS-EPHE-UPVD, Biologie et Ecologie Tropicale et Méditerranéenne, Université de Perpignan Via Domitia, 52 Avenue Paul Alduy, 66860 Perpignan Cedex, France
[c] Malta Centre for Fisheries Sciences, Fort San Lucjan, Marsaxlokk BBG 06, Malta
[d] Grupo de Investigación Ecología y Ordenación de Ecosistemas Marinos Costeros, Departamento de Ecología e Hidrología, Universidad de Murcia, Campus de Espinardo, 30100 Murcia, Spain
[e] Groupement d'Intérêt Scientifique (GIS) Posidonie, Parc Scientifique et Technologique de Luminy, 13288 Marseille Cedex 9, France
[f] Departamento de Oceanografia e Pescas, Universidade dos Açores, PT-9901-862 Horta, Portugal
[g] CEFAS, Marine Environmental Management, Pakefield Road, Lowestoft NR33 OHT, UK

A R T I C L E I N F O

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A B S T R A C T

We examined the spatial dynamic of artisanal fishing fleets around five European marine protected areas (MPAs) to derive general implications for the evaluation of MPAs as fisheries management tools. The coastal MPAs studied were located off France, Malta and Spain and presented a variety of spatial designs and processes of establishment. We developed a standardized methodology to define factors influencing effort allocation and to produce fishing effort maps by merging GIS with geostatistical modelling techniques. Results revealed that in most cases the factors "distance to the no-take", "water depth", and "distance to the port" had a significant influence on effort allocation by the fishing fleets. Overall, we found local concentration of fishing effort around the MPA borders. Thus, neglecting the pattern of fishing effort distribution in evaluating MPA benefits, such as spillover of biomass, could hamper sound interpretation of MPAs as fisheries management tools.

1. Introduction

Worldwide the location and implementation of marine reserves, marine protected areas (MPAs) and "no-take zones" becomes increasingly important, as traditional fisheries management has failed to safeguard declining fish stocks (Pauly et al., 2002; Hilborn et al., 2004). By removing fishing pressure from specific areas and regulating fisheries in the surrounding waters, managers and stakeholders expect to enhance fishing yields and to conserve marine habitats at the same time (Allison et al., 1998; Lauck et al., 1998). Enhancement of fishing yields can originate by a net export of adult biomass (spillover effect) and/or larvae (recruitment effect) from the marine reserves outwards into the adjacent waters (Russ and Alcala, 1996; Roberts et al., 2001; Russ, 2002). Moreover, these fisheries benefits operate at different spatial scales. While spillover effects occur rather close to MPAs (from 1–10 up to 100 km), larval dispersal may be significant farther away, from 10 to 100 km for invertebrates and 50 to 200 km for fish (Palumbi, 2004).

Although evidence exists from theoretical (Demartini, 1993) and empirical studies (Abesamis et al., 2006) that the contribution of biomass spillover to the total fisheries catch is small to moderate, this fisheries effect could play a critical role in convincing stakeholders to support the establishment and maintenance of MPAs (Russ, 2002). The actual contribution of spillover to total fisheries yield can be counteracted by high fishing intensity bordering the MPA. A study by McClanahan and Mangi (2000) demonstrated, that intense fishing near the borders of a marine reserve has the potential to reduce catch rates and hamper the evaluation of its effectiveness in terms of biomass export. Also, a modelling study by Walters (2000) showed that the spatial distribution of fishing effort likely has the potential to reduce the success of small MPAs.

While many MPAs worldwide have been implemented in various ecosystems, studies that evaluate the spatial redistribution of effort by fishermen in response to the imposition and placement of new borders are still lacking (Smith and Wilen, 2003; Wilcox

* Corresponding author. Address: CEFAS, Marine Environmental Management, Pakefield Road, Lowestoft NR33 OHT, UK. Tel.: +44 1502 527779.
E-mail address: vanessa.stelzenmuller@cefas.co.uk (V. Stelzenmüller).

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and Pomeroy, 2003). Effort redistribution can be critically important to achieving management objectives, especially when fishing effort concentrates near the boundaries of a marine reserve or fishing closure (Halpern and Warner, 2003; Halpern et al., 2004). As a result, the behaviour of the fishermen in concentrating effort near the borders and locally increasing fishing pressure raises concerns from two points of view (1) biologically, by reducing the potential for reproductively mature fish to become established outside the MPA, and (2) socio-economically, by reducing the number of fishermen benefiting from the MPA (McClanahan and KaundaArara, 1996). Thus, understanding the spatial patterns of fishing effort around MPAs is crucial to evaluating the fisheries benefits of reserves.

Many factors could influence the spatial allocation of fishing effort, such as (a) spatial distribution of the fishery stocks, (b) the differential value of various target species, (c) weather conditions, (d) social factors such as local traditions or agreements among stakeholders and managers, and/or, (e) the location of the MPA with respect to fishing ports (Wilcox and Pomeroy, 2003; Abesamis et al., 2006). For instance, the fishermen's decisions about transit to fishing grounds near MPAs will reflect their expectations of improved fishing conditions and also the distance to the port, a component of operating cost. Thus, the overall allocation of fishing effort may be affected by the presence of an MPA, by its accessibility and by the location of other fishing grounds representing different types of habitat and target species.

A number of simulation studies incorporate patterns of fishing effort to predict the potential of MPAs to enhance fisheries (Walters, 2000; Zeller and Reinert, 2004; Martell et al., 2005). However, only a very few empirical studies have taken into account the spatial distribution of fishing effort in order to evaluate catch data obtained from the waters surrounding MPAs or fishing closures (Murawski et al., 2005). In general, studies investigating spatial patterns of fishing effort recovered from log book records or vessel monitoring data (VMS) use geographical information systems (GIS) for mapping purposes (Murawski et al., 2005) and/or utilize grid-based numeric operations to assess geo-referenced information on fishing activity (Ragnarsson and Steingrimsson, 2003; Lynch, 2006). In contrast, fleet dynamics and the response to regulation are principally analysed by bio-economic models (Soulie and Thebaud, 2006).

In nature, organisms are distributed neither uniformly nor at random. Rather they are aggregated in patches or other kinds of spatial structures (Legendre and Fortin, 1989). Fish targeted by any fisheries form associations depending on the species (Fernandes and Rivoirard, 1999), size and age class (Wieland and Rivoirard, 2001), seasonality (Rueda and Defeo, 2001) or habitat association (Stelzenmüller et al., 2005, 2007). As the occurrence of the targeted species is often reflected in the spatial patterns of the corresponding fishing activity (Swain and Wade, 2003), fishing effort data can be characterised by a high level of spatial heterogeneity. This spatial structuring could cause a spatial autocorrelation within the data, justifying the need to approach the problem through geostatistical methods (Cressie, 1991).

In this study we aim to investigate spatial patterns and trends in fishing effort allocation within the vicinity of five European MPAs or fisheries management zones having different spatial designs off France (Banyuls and Carry-le-Rouet), Malta, and Spain (Cabo de Palos and Medes Islands). In all cases, local fishing activities are restricted to artisanal fisheries, which are often coastal, involving small capital investment and boats smaller than 12 m (Colloca et al., 2004). In general, artisanal fisheries are characterised by highly diverse fishing gear and diverse target species, as well as by marked seasonality determined by the local fishermen's knowledge of the species behaviour and abundance throughout the year.

To assess the spatial dynamics of the fishing fleets operating around the coastal MPAs or fisheries management areas we developed an integrated approach, merging GIS (Burrough and McDonnell, 1998) with geostatistical and multivariate techniques (Venables and Dichmont, 2004). Within a GIS we modelled the spatial distribution of effort density as a function of various explanatory variables reflecting habitat characteristics or economic aspects that could *a priori* influence effort allocation. At the same time, we took the spatial structuring of the data into account. Because continuous spatial data are gaining importance for conservation planning and resource management, we mapped the estimated spatial distributions of effort density (Vaz et al., 2008) for each case study.

For our analyses we used catch positions recorded in the course of onboard samplings (2000–2005), as well as data records from the Maltese fisheries management system (2005). With this work we contribute to the few existing empirical studies analysing spatial patterns and trends of fishing effort around MPAs. Knowledge of these patterns is fundamental for sound evaluations of MPAs as fisheries management tools.

For the representative artisanal fishing fleets operating around the five MPAs in our study, we addressed the following research questions: (1) Which explanatory variables most influenced the fishing effort allocation around the MPAs? (2) Does the fishing effort density concentrate close to the border of the MPA or fisheries management zone? (3) What are the possible general implications for the evaluation of the MPAs as fisheries management tools?

2. Methods

2.1. Case studies

We investigated the fishing effort around five European MPAs established between 1974 and 2004 with the main purposes of protecting marine habitats and regulating local fisheries (Fig. 1; Table 1). These MPAs are in coastal zones or near island shores representing typical Mediterranean habitats, such as rocky reefs, sandy and mud bottoms, and *Posidonia oceanica* beds. The MPAs selected differed in their spatial designs, size and year of establishment (Table 1). The MPAs of Cerbère-Banyuls (1; Fig. 1), Cabo de Palos (2; Fig. 1), and Medes Islands (5; Fig. 1) consist of a no-take zone, where fishing is prohibited, and a partial take zone where the fisheries are restricted (see below for more details). In contrast, the MPA of Carry-le-Rouet (3; Fig. 1) comprises only a no-take zone. We considered Malta with its 25 nautical mile (nm) fisheries management zone (FMZ) as an MPA (4; Fig. 1) with a partial take zone limited by the 12 nm zone.

For all of the case studies, fisheries in the partial take zones were restricted to artisanal fisheries involving vessels smaller than 12 m. The artisanal fleets use a whole range of fixed or mobile gears, such as gillnets, trammel net, longlines, trap nets, and drift nets (only in Malta). The target species vary with season and belong mostly to the families Sparidae, Scorpaenidae, Mullidae, Gadidae and Soleidae.

2.2. Data collection

We collected fishing effort data onboard the fishing vessels operating in the vicinities of the MPAs (except Malta; Table 2). Between the years 2000 and 2005 we recorded positions of fishing gear deployments (using GPS), type of fishing gear, local depth and type of bottom only from those vessels conducting a continuous fishery throughout the years. In cases for which less than 100% of the continuously active fishing fleet was sampled, boats were

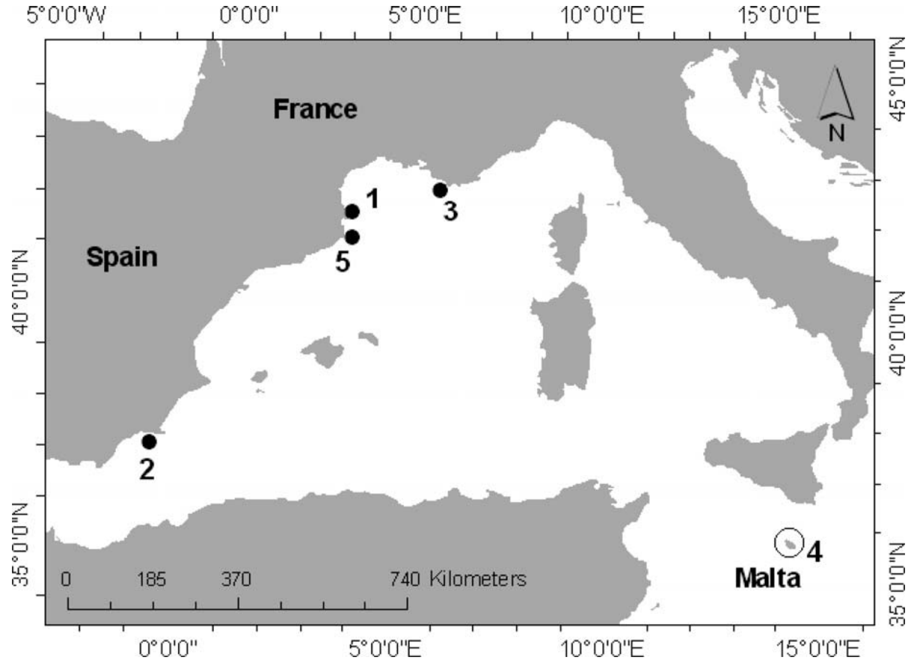

Fig. 1. Spatial location of the five European MPAs involved in this study.1: Cerbère-Banyuls (France); 2: Cabo de Palos (Spain); 3: Carry-le-Rouet (France); 4: Malta; 5: Medes Islands (Spain).

Table 1
Year of establishment, size, depth range and habitats of the studied MPAs: Cerbère-Banyuls (Banyuls), Cabo de Palos (CDPalos), Carry-le-Rouet (Carry), Malta and the Medes Islands (Medes)

MPA	Year of establishment	Total size/no-take zone (ha)	Depth range (m)	Habitats
Banyuls	1974	617.4/65	0–60	Rock reef, coralligenous
CDPalos	1995	1898/270	0–100	*P. oceanica* beds, rocky reefs, sandy bottoms, detritic bottoms
Carry	1983	210 (Cap Couronne)/85 (Carry)	0–34	*P. oceanica* beds, rocky reefs, sandy bottoms
Malta	2004	1070000/–	0–1200	*P. oceanica* beds, sandy bottoms, offshore habitats, reefs
Medes	1983	511/93	20–60	*P. oceanica* beds, rocky reefs, sandy bottoms, mud

Table 2
Years of sampling, total number of artisanal fishing vessels, number of vessels sampled, percentage of fleet sampled, the total possible fishing effort per year, the fishing effort sampled, percentage of total fishing effort sampled, the resolution of the summary grids, and the resolution of the prediction grids for the MPAs of Cerbère-Banyuls (Banyuls), Cabo de Palos (CDPalos), Carry-le-Rouet (Carry), Malta, and the Medes Islands (Medes)

MPA	Years of sampling	Number of total vessels/sampled vessels	Percent of fleet sampled	Total effort (days × boats/ year)[a]	Effort sampled (days × boats)[b]	Percent of total effort sampled[c]	Summary grid cell resolution (m)	Prediction grid cell resolution (m)
Banyuls	2000, 2001, 2003, 2004	6/6	100	1145	286	74.7	500	50
CDPalos	2003, 2004	>15/4	<26	5735	102	8.6	750	100
Carry	2003, 2004	13/11	85	3063	150	41.6	250	50
Malta	2005	>1000					9200	(9200)
Medes	2003, 2004, 2005	24/7	29	5742	166	15.2	500	50

[a] Total effort: (Σmean number of days of gear deployment$_{Gear}$ × Σnumber of boats$_{Gear}$)/year.
[b] Effort sampled: Σnumber of days of gear deployment$_{Gear, Year}$ × Σ number of boats$_{Gear, Year}$.
[c] Percent of total effort sampled: effort sampled/(total effort × number of sampling years) × 100.

selected randomly. However, the fishermen's willingness to collaborate also played a crucial role in the selection of boats.

We calculated the annual total fishing effort in the vicinity of the MPAs as the mean number of days of gear deployment multiplied by the number of boats employing a specific gear type (see Table 2). Further, we calculated the fishing effort sampled in a given time period in the same unit (days × boats) by multiplying the number of days that a gear was employed by the number of sampled boats employing that gear. This allowed us to compute the percentage of the total fishing effort sampled (9–75%; Table 2). In Malta all fishermen of the artisanal fleets considered here are obliged to report their catch positions, which are stored in the fisheries management system (see below for further descriptions).

2.3. Spatial analysis of fishing effort – integrated GIS approach

We explored the general spatial patterns of the fishing activity around five European MPAs and their controlling factors by merging GIS with geostatistical and generalized additive models

(GAMs). We describe the general approach in the following text and then give specific details for each case study.

In the GIS we superimposed grids with cell sizes, from 250 m by 250 m to 750 m by 750 m, respectively (Table 2), that were compromises between the length of the fishing sets and size of the study area. We aggregated all fishing gear positions without further stratification by fishing gear or season and summarized the number of fishing gear deployments recorded by grid cell or extracted from data on fishing effort from the Maltese fisheries management system. We calculated a measure of effort density (ED_i: number of gear deployments km^{-2}) by dividing the number of fishing gears per grid cell by the surface area (km^2) of a grid cell.

For each case study, we defined spatial objects presumably having an influence on the fishing effort allocation. The data for these spatial objects represented results of former studies or were created for this analysis. In all cases (except for Malta) we defined the spatial objects "border of no-take zone" and "the nearest port", but in each case we selected various additional objects (e.g., sea grass beds, biomass hot spots, etc.; see below for details). In the GIS we then calculated the shortest linear distances from the midpoint of the respective grid cells to discrete spatial objects, thus we created explanatory variables such as "distance to MPA", "distance to port". Further, we defined for each case (except Malta) a high resolution prediction grid and calculated the same explanatory variables for each cell in it. We kept the cell size of the prediction grids to a maximum of 10% of the summary grid cells to avoid grid resolutions less than half the length of a short fishing set (e.g., 100 m) (Table 2).

With the help of GAMs (Hastie and Tibshirani, 1986) we determined from the suite of explanatory variables those apparently having a significant influence on the fishing effort allocation in the respective study areas. A GAM model is a best-fit approximation of effort density (ED) as a function of the explanatory variables. GAMs implemented in a GIS are commonly used in landscape ecology to model and predict the spatial distribution of animals (Maggini et al., 2006; Randin et al., 2006). This modelling technique for predicting spatial distribution of variables like abundance indices or effort densities is rather uncommon in fisheries science. Classically, in fisheries, GAMs are used to standardize catch data (Maunder and Punt, 2004) or determine significant predictor variables (Linlokken and Haugen, 2006). Only recently have studies like that by Sacau et al. (2005) combined the use of GAMs with a GIS.

From the full set of calculated models, we selected the best models (and thereby the explanatory variables most likely responsible for the particular fishing effort allocation within the study areas) by the lowest value of Akaike information criterion (Akaike, 1973).

Predictive modelling is gaining more importance, especially in resource management and conservation planning, as continuous spatial information helps to reduce spatial conflicts among stakeholders or user groups. For that reason we not only defined the factors influencing fishing effort, we also estimated general maps of fishing patterns. That is, we used the selected GAMs and their respective explanatory variables to predict a value of effort density for each cell of the prediction grid (generating a trend map).

Spatial autocorrelation in the effort density data could lead to local over- or under-estimation of effort densities by the GAMs; therefore, we corrected these estimates by conducting a geostatistical analysis of the GAM residuals. To describe the spatial structure present within the residuals we computed omnidirectional semivariograms, using the robust "modulus" estimator (Cressie and Hawkins, 1980), which outline the spatial correlation of data by calculating the semivariance between data points as a function of their distance. We fitted parameters of spherical models (nugget effect, sill and range) with the help of a weighted least squares fitting procedure and predicted then continuous maps of the residuals (autocorrelation map) using ordinary point kriging (Cressie, 1991).

Finally, we combined the respective trend and autocorrelations maps to produce continuous maps of general effort densities. This "hybrid" interpolation method is also referred to as "regression kriging" (Hengl et al., 2004). In many cases, kriging combined with regression has proven to be superior to the common geostatistical techniques, yielding more detailed results and higher accuracy of prediction (Knotters et al., 1995). This approach was applied to all of our case studies (with modifications in the case of Malta). In the following we describe in more detail the individual types of data used and the spatial objects defined.

Cerbère-Banyuls – In the case of Cerbère-Banyuls we calculated the explanatory variables as the nearest linear distance (m) 1) to the no-take zone (disMPA), 2) to the nearest port (disPort), and 3) depth (m).

Cabo de Palos – In the GIS of Cabo de Palos we buffered each gear deployment position by 10% of the measured net length to account for possible uncertainty in the position of the gear deployment. We calculated the explanatory variables as the nearest linear distance (m): (1) to the no-take zone (disMPA), (2) to *P. oceanica* beds (disPos), (3) to the port of Cabo de Palos (disPort), (4) to the zone with fine sand bottom (disFS), (5) to the zone with *Cymodocea* (disCym), (6) to the zone with coralligenous bottom (disCor), (7) to the zone with contaminated mud (disMudco) and (8) to the zone with detritic bottom (disDet).

Carry-le-Rouet – We buffered the spatial locations of the gear employments with 10% of the net length to account for uncertainty in the locations of gear deployment. We computed the following explanatory variables as the nearest linear distance (m): (1) to the no-take zone (disMPA), (2) to artificial reefs (disAR), (3) to the port of Carry-le-Rouet (disPort), (4) to *P. oceanica* beds and (5) depth (m).

Malta – The fishing activities in 2005 in the FMZ of Malta were already attributed to three standard grids having a resolution of 5 min (latitude × longitude) (∼9260 m by 7395 m), 20 min (∼37,040 m by 30,708 m) and 1° (∼111,120 m by 88,744 m). Within the 12 nm zone, we extracted data on fishing effort from these different grids of the fisheries management system. We then summarized data on effort density for 5 min grid cells as follows: (1) for each grid cell (three standard grids) we defined fishing effort (FE) as number of deployments × gear units (pieces of net; number of hooks), and we calculated effort density (ED_{Malta}: number of deployments × gear units km^{-2}) by dividing FE by the area of a grid cell, (2) we divided FE values attributed to the 1° cells by 144 and FE_{144} and added them to the respective 5 min grid cells and (3) we divided FE values attributed to the 20 min cells by 16 and FE_{16} and added them to the respective 5 min grid cells ($FE_{5\ min} = FE + FE_{144} + FE_{16}$; $ED_{5\ min} = FE_{5\ min}$/surface area of 5 min grid cell). We calculated effort densities separately for the two main artisanal fishing fleets only employing boats with a length $\leqslant$ 12 m the trammel net ($ED_{MaltaTL}$) and bottom longline ($ED_{MaltaBL}$) fleets.

For Malta we used the explanatory variables depth (m), derived with the help of kriging, and the nearest linear distance (m): (1) to the nearest port contributing $\geqslant$5% to the overall fleet registration (Buggiba, Marsaskala, Marsaxlokk, Msida, St. Julians Bay and St. Pauls Bay) (disPort) and (2) to a hot spot area southeast of Malta where consistently high biomass of bony fish was found (disDSH). Additionally, we roughly attributed a bottom type to each grid cell to test the influence of the former on the effort density of the fleets. The mapped effort densities reflect the respective summarized fishing effort per 5 min grid cell. We also combined the bottom longline and trammel net fishing effort by reclassifying the respective effort density maps into a dimensionless scale of effort density and we then added these reclassified maps (more details on map algebra and raster maps can be found in Burrough and McDonnell, 1998).

Medes Islands – We compensated uncertainty in the spatial location of the fishing gear by defining a coarse grid, 500 m by 500 m (see Table 2). We computed the following explanatory variables as the nearest linear distance (m): (1) to the no-take zone (disMPA), (2) to artificial reefs (disAR), (3) to the port of L'Estartit (disPort), (4) to *P. oceanica* beds, (5) depth (m) and (6) the mouth of the river Ter (disRiver).

3. Results

3.1. Driving forces of fishing effort allocation

In total, we computed 105 multivariate GAMs (Cerbère-Banyuls: 4, Cabo de Palos: 51, Carry-le-Rouet: 21, Medes Islands: 17, Malta: 12) by combining only the explanatory variables showing low levels of correlation to avoid the effect of co-linearity on the modelling processes. In Table 3 all of the selected GAMs are summarized together with the relevant explanatory variables. We selected the final GAMs by the lowest AIC value, finding models that explained between 38.3% and 78.3% of the overall data variability. For all case studies (except for Malta) we could identify the variables disMPA and depth as having a significant influence on the effort allocation by the distinct fishing fleets. Furthermore, we found the variable disPort, which relates to effort costs to the fishermen, to be significant in the models of the French and Maltese MPAs. In none of the cases were disPos or disAR found to be significant. The fitted spline functions for the predictor variables incorporated in the final GAMs for ED are presented in Fig. 2. In the cases of Cerbère-Banyuls, Cabo de Palos and Medes Islands we identified clear decreases of ED with increasing distance to the MPA border. In contrast, we observed clear decreases of ED in Carry-le-Rouet and Malta with increasing distance to the port(s). Around the reserves of Cerbère-Banyuls and Medes Islands we observed decreasing intensities of fishing activity with increasing depth, but we found more complex responses of ED to depth around Cabo de Palos and Carry-le-Rouet. We also derived threshold values from fitted spline functions (see Fig. 2), where a positive effect of an explanatory variable on the respective ED values could be expected. These threshold values together with important spatial scales and ranges of values are listed in Table 4. We observed that distances to the no-take zones or ports at which effort densities decreased might be related to MPA size.

Table 3
Final selected effort density (ED) GAMs for Cerbère-Banyuls (Banyuls), Cabo de Palos (CDPalos), Carry-le-Rouet (Carry), Malta bottom longlines (MaltaBL), Malta trammel nets (MaltaTL), and Medes Islands (Medes)

Explanatory variables	$ED_{Banyuls}$	$ED_{CDPalos}$	ED_{Carry}	$ED_{MaltaBL}$	$ED_{MaltaTL}$	ED_{Medes}
disMPA (m)[a]	**S**[i]	**S**	**S**			**S**
disPort (m)[b]	**S**	–	**S**	**S**	**S**	–
disPos (m)[c]		–	–			–
disAR (m)[d]			–			–
Depth (m)	**S**	**S**	**S**	–	–	**S**
disRiver (m)[e]						**S**
disDHS (m)[f]				**S**	S	
disDet (m)[g]		**S**				
Bottom type				**S**	**S**	
AIC[h]	762.08	311.81	2385.9	1437.365	618.1836	496.47
Deviance explained (%)	53.7	57.9	57.4	66.5	78.3	38.3

[a] disMPA, distance to no-take area.
[b] disPort, distance to nearest port(s).
[c] disPos, distance to *P. oceanica* beds.
[d] disAR, distance to artificial reef zone.
[e] disRiver, distance to River mouth.
[f] disDHS, distance to biomass hot spot.
[g] disDet, distance to detritic bottom.
[h] AIC, value of Akaike's information criterion.
[i] Explanatory variables contained in the selected models are indicated with S and with – otherwise. Significance (p-value < 0.05) of the variables within the models is indicated with S in bold.

3.2. Spatial distribution of fishing effort

The maps of estimated fishing effort densities around the MPAs of Cerbère-Banyuls, Cabo de Palos, Carry-le-Rouet and Medes Islands are presented in Fig. 3a, while the maps for Malta are presented in Fig. 3b.

We found locally concentrated ED around the borders of all no-take zones (Fig. 3a), which results in rather heterogeneous effort distributions. In the case of Cerbère-Banyuls (Fig. 3a; top left) we calculated the highest ED at the northern and southern borders of the no-take zone, indicating steep east–west gradients in ED within the partial take zone. Further, within the study area around Cabo de Palos (Fig. 3a; bottom left), we estimated the highest ED at the north-western border of the no-take zone as well as some patches of homogenous effort density in the eastern part of the study area, also reflecting a steep north–south gradient in ED around the no-take zone.

For Carry-le-Rouet (Fig. 3a; top right) we discovered a general concentration of effort density at the eastern and western borders of the no-take zone close to the coast showing homogenous fishing effort densities from the no-take zone outwards. As a consequence, we found steep north–south gradients in effort densities. Around the no-take zone of the Medes Islands (Fig. 3a; bottom right) we found patches of highest effort concentration very close to its western border. Thus, we observed within the partial take zone a clear difference of fishing pressure between the eastern and the western side. We could define steep east–west gradients of effort density in the northern part of the partial take zone. In Fig. 3b the spatial dynamics of the two most representative artisanal fishing fleets of Malta are presented. We recovered a general concentration of the artisanal fishing activity within the 12 nm zone and found highest effort densities within the 3 nm zone. While we observed concentrated bottom longline effort densities near the main port of Marsaxlokk (Fig. 3b; top left), we mapped aggregated trammel net effort densities (Fig. 3b; top right) near the ports of Buggiba and St. Paul Bay. A qualitative map showed highest fishing pressure within the 3 nm zone around Malta (Fig. 3b; bottom left).

4. Discussion

One of the current needs for sustainable fisheries is the appraisal of MPAs as management tools in different marine systems. To reach this goal, a profound understanding of the spatio-temporal dynamics of the fishing fleets involved is essential. We must consider the impact of fishing effort and its distribution on catches in the surrounding waters, and we must assess the degree to which spillover is taken by fishermen, diminishing the contribution of spillover to overall biomass.

With the help of our integrated GIS approach, we found for the artisanal fisheries around five MPAs that the explanatory variables distance to the no-take zone, distance to the nearest port and depth were significant for effort allocation. That was also reflected in our estimated fishing effort maps that show concentrated effort densities around the borders of the no-take zones producing heterogeneous patterns and steep-gradients of fishing effort within the study areas.

These results need to be interpreted in relation to the percentage of the total fishing effort sampled. In the case of Malta, 100% of

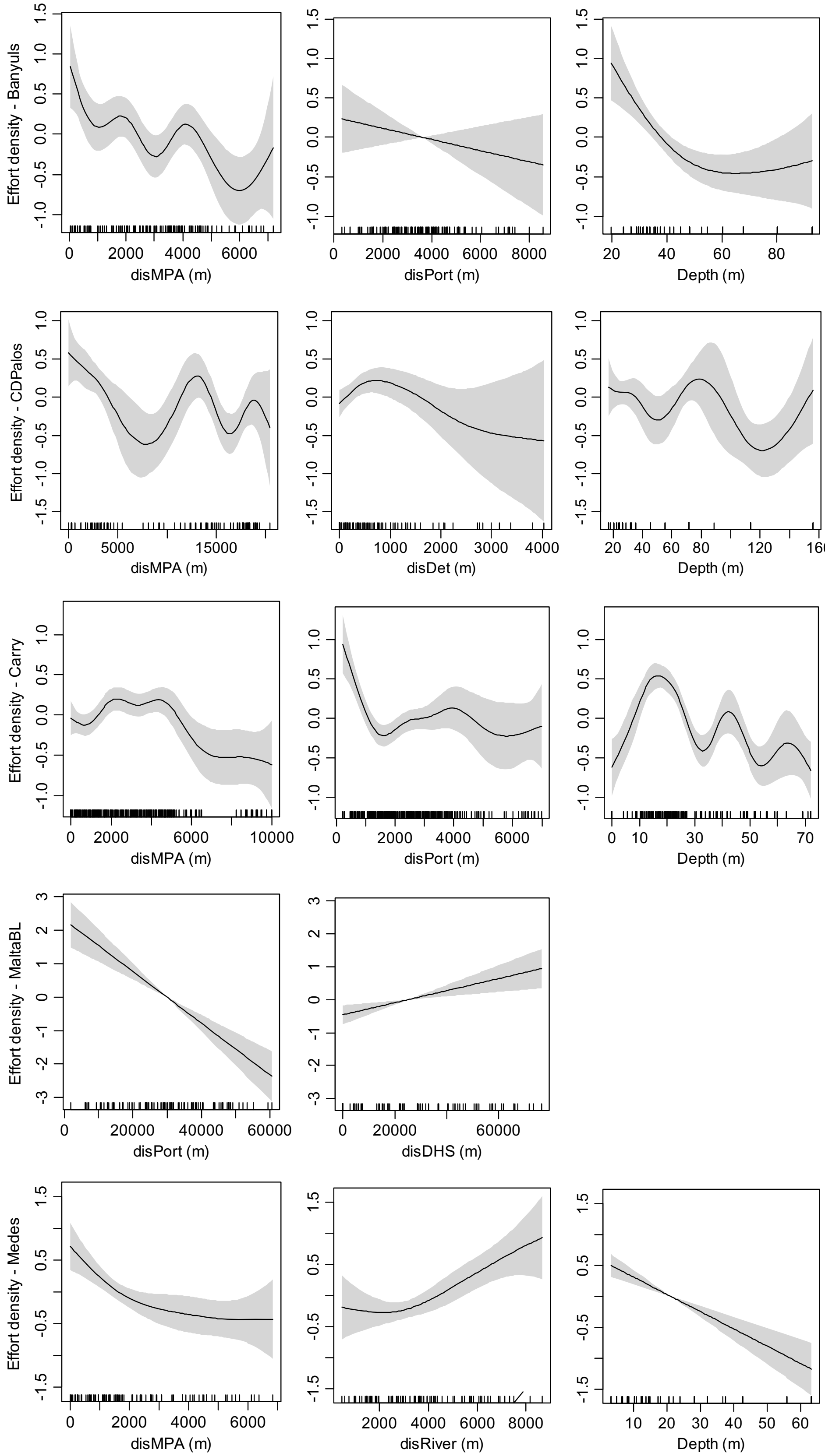

Fig. 2. Additive fits of the predictor variables incorporated in the selected effort densities GAMs of Cerbère-Banyuls (Banyuls), Cabo de Palos (CDPalos), Carry-le-Rouet (Carry), Malta (MaltaBL; bottom longline) and Medes Islands (Medes). Tick marks above the *x*-axis indicate the distribution of observations. Confidence bands (95%) around the predictions are shaded in grey. A positive effect on effort densities is shown when the curve (with confidence intervals) lies within the positive side of the *y*-axis.

the fishing effort of the artisanal fishing fleets we studied was recorded by the fisheries management system; therefore, we have a high level of confidence in the identified driving factors and corresponding maps. The results for the French MPAs rank next

Table 4
Important spatial scales of the MPAs for Cerbère-Banyuls (Banyuls), Cabo de Palos (CDPalos), Carry-le-Rouet (Carry), Malta, and the Medes Islands (Medes) and threshold values[a] extracted from the fitted effort density GAMs (see Fig. 2)

MPA	Total size/no-take area (ha)	Thresholds disMPA (km)	Thresholds disPort (km)	Thresholds depth (m)
Carry	210 (Cap Couronne/85 (Carry)	0–2.0	0–1.7	10–30
Medes	511/93	0–1.8	–	20
Banyuls	617.4/65	0–2.5	0–3.0	40
CDPalos	1898/270	0–5.0	–	60–100
Malta	1070,000/–	–	0–30.0	–

[a] The thresholds reflect the range of values were the variables have a positive effect on the effort density estimates.

for confidence, as we sampled 42% (Carry-le-Rouet) and 75% (Cerbère-Banyuls) of the total possible fishing effort during their respective study periods. We attribute the lowest level of confidence to the results for the Spanish MPAs where only 7% (Cabo de Palos) and 15% (Medes Islands) of the total possible fishing efforts were sampled.

Confidence in the reality of the patterns aside, the interpretation of the observed patterns is rather complex. Some studies suggest that the occurrence of high fishing activity around the borders of MPAs indicates the spillover of adult biomass occurring already (Gell and Roberts, 2003), while other studies suggest that concentration of effort adjacent to MPAs is caused by the fishers' expectation of adult fish biomass export (Wilcox and Pomeroy, 2003). Thus, the distribution of effort density could build a barrier for biomass spillover (McClanahan and KaundaArara, 1996). It is obvious that the observed general pattern of ED distribution and the importance of distance to the no-take zone as an explanatory variable could reflect various factors, such as the effect of spillover of biomass resulting in increased yields, the catch of larger-sized individuals (which also results in increased revenues), a trade-off between travel costs and catch (depending on the location of the MPA), the main target species of the fishery concentrating around the MPA (see, e.g., Abesamis et al., 2006), or a combination of these factors. In contrast, the distance to the nearest port relates to the compromise between the costs and yield of a fishing trip, a compromise that fishermen must take into account. In turn, this could depend on the seasonality of the targeted species and variable fuel and fish market prices. The selected variable depth seems to reveal preferred fishing grounds, which could be associated with certain fish assemblages. With our integrated approach we found that fitted GAMs could explain only 38% (Medes Islands) to 78% (MaltaTL) of the overall data variability. Hence, it seems that factors not considered in the analysis also influence the effort allocation of the artisanal fleets. Those could be, for instance, weather conditions

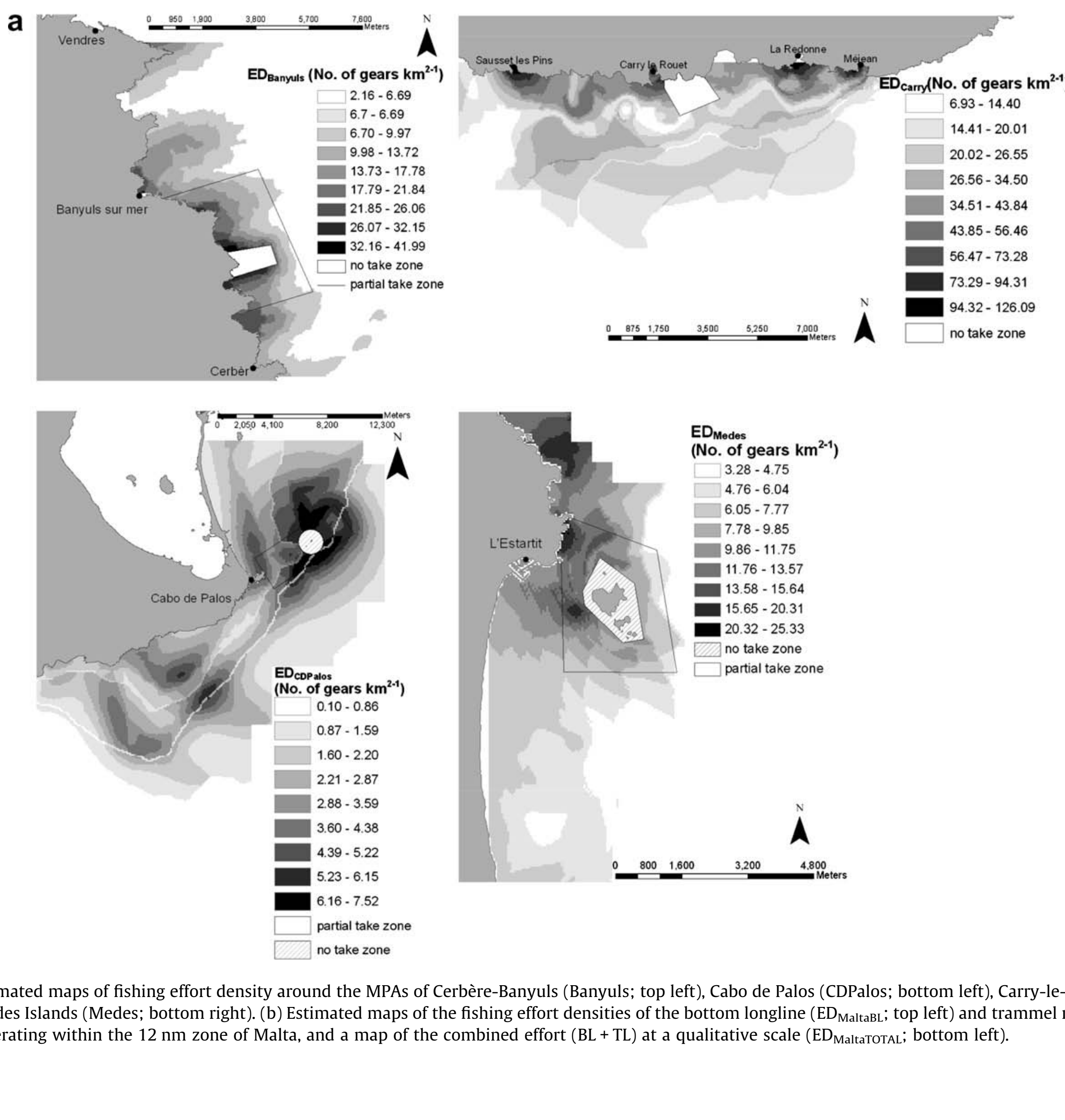

Fig. 3. (a) Estimated maps of fishing effort density around the MPAs of Cerbère-Banyuls (Banyuls; top left), Cabo de Palos (CDPalos; bottom left), Carry-le-Rouet (Carry; top right), and Medes Islands (Medes; bottom right). (b) Estimated maps of the fishing effort densities of the bottom longline ($ED_{MaltaBL}$; top left) and trammel net ($ED_{MaltaTL}$; top right) fleet operating within the 12 nm zone of Malta, and a map of the combined effort (BL + TL) at a qualitative scale ($ED_{MaltaTOTAL}$; bottom left).

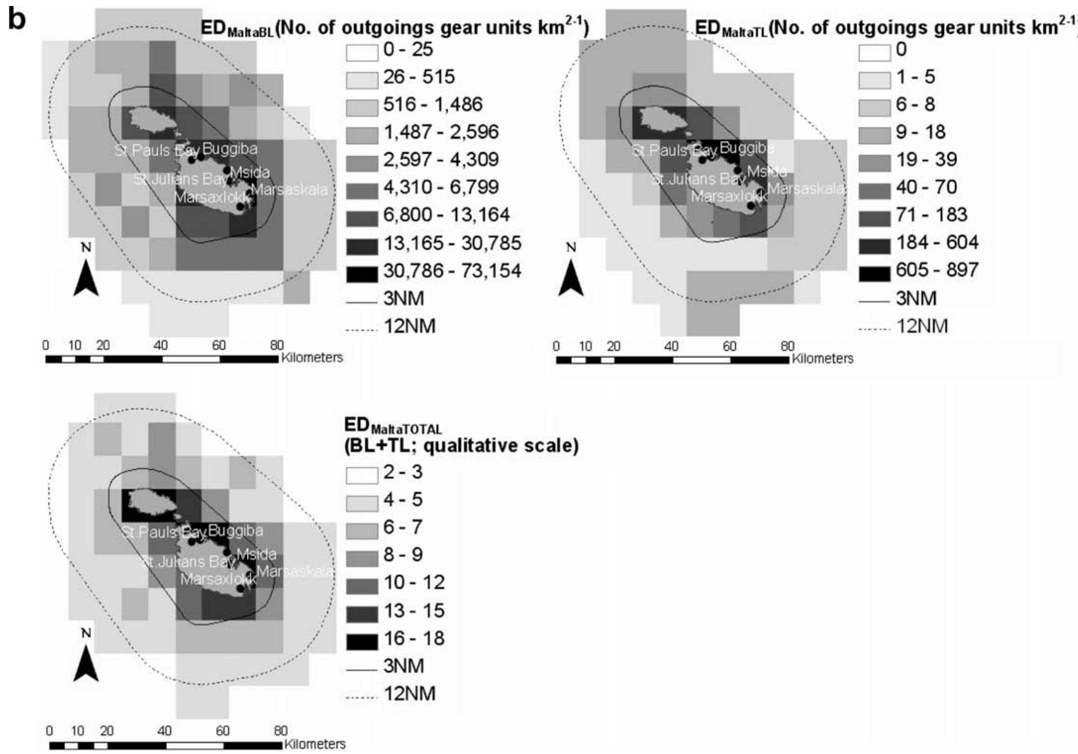

Fig. 3 (*continued*)

and/or social factors like local agreements and traditions (Wilcox and Pomeroy, 2003).

In all cases (except Malta), estimated maps showed ED concentrated around the borders of the respective no-take zones, resulting in steep-gradients of ED. The estimated maps of ED are based on the aggregated information on gear deployment positions and reflect, therefore, mean patterns of fishing effort allocation around the studied MPAs all through the respective study periods (3–4 years). Seasonal deviations from estimated absolute values and patterns can be expected. In future studies further stratification of sampling data, e.g., by gear employed could lead to a more profound understanding of the fishing effort dynamics. However, we developed a standardized approach, allowing comparisons at a European scale, assessment of general patterns of ED around MPAs and determination of driving factors.

4.1. Implications for fisheries management

Empirical studies focusing on the evaluation of MPAs as fisheries management tools often neglect the spatio-temporal dynamics of the fishing fleets involved, which could hamper sound interpretation of reserve effectiveness.

For instance, since the implementation of controls on the temporal dynamics of fishing effort, Roberts et al. (2001) found a significant increase in catches in the vicinity of a Caribbean MPA. Further, a modelling study by Smith (2004) demonstrated that, for a heavily exploited fishery, when the heterogeneous distribution of fishing effort around MPAs is ignored, yield-per-recruit models overestimated yield gains from the creation of the reserve. Therefore, ignoring the patchy distributions of concentrated effort densities observed in this study could lead to general overestimations of fishing yields around the no-take zones. That would lead in turn to a biased assessment of the fisheries benefits of the respective MPAs. Our results show the necessity of an integrated approach, combining the spatial assessment of fishing effort and fisheries benefits, as a main requisite for successful fisheries management of MPAs. This is in line with a study of Babcock et al. (2005), who discusses the need for spatialized indicators in ecosystem-based fishery management. The second implication for successful fisheries management is the use of GIS frameworks, where maps of fishing effort densities can be overlaid with maps of other human pressures such as tourist activities or conservation measures, allowing assessment of the potential for spatial conflicts.

One condition indicating fisheries benefits in terms of resource spillover from a no-take zone is a resource biomass density gradient, declining from the its border toward the surrounding waters (McClanahan and Mangi, 2000). Plots of catch data vs. distance to MPA can show complex relationships at multiple distance scales due to the confounding effects of environmental factors (such as habitat heterogeneity) and behavioural adaptations to seasonally varying environment (Murawski et al., 2003). The determination of the appropriate spatial scale for measuring fisheries benefits is a crucial point in the process of a MPA evaluation. The thresholds derived here (see Table 4) indicated a general increase of significant spatial scales with increasing MPA sizes. Moreover, in cases where the variable "distance to the no-take zone" (disMPA) was significant, the threshold values obtained could serve as indicators for appropriate spatial scales to measure fisheries benefits such as the spillover of adult biomass to the surrounding waters. Therefore, an important implication of our results for a sound assessment is the use of a methodology allowing determination of the spatial scales relevant to the fisheries to be studied.

Although, this study included only five MPAs, we suggest that the patterns found likely apply generally for coastal MPAs where artisanal fishing fleets operate in the surrounding waters. Thus, we conclude that neglecting the pattern of fishing effort distribution in the process of measuring reserve benefits, e.g., the spillover of biomass, could hamper the sound evaluation of MPAs as fisheries management tools. Moreover, our integrated approach to assess pattern of fishing effort can support a standardized evaluation of MPAs as fisheries management tools.

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