Mapping the potential locations of European hake (Merluccius merluccius) nurseries in Italian waters

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Mapping the potential locations of European hake (*Merluccius merluccius*) nurseries in the Italian waters

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Abstract

A geostatistical approach was used to pinpoint the main nursery areas of demersal resources and define their persistence by means of direct estimation of fish densities. The European hake (*Merluccius merluccius* Linnaeus, 1758), one of the most important demersal resources inhabiting the whole Mediterranean from 30 metres (m) to almost 1000 m depth, was used as a case study to locate their recruits and check their stability using geo-spatial methods and common criteria. Data were collected during trawl surveys carried out in the late-spring and autumn from 1994 to 2006 in seven geographical sub-areas (GSAs) including Italian waters in the Western and Central Mediterranean.

Indicator kriging was applied to locate the sites where number of recruits exceeded, at a given probability, a conditioned threshold value. The temporal persistence of high-density patches of recruits was then evaluated by means of an index of spatial persistence. Hake recruits showed patchy distribution with several denser areas showing a high temporal persistence. The main nursery areas were identified in the Central Adriatic Sea (GSA17), northern Tyrrhenian–Ligurian seas (GSA 9) and Sardinia (GSA 11). Important nurseries occurred also in the Strait of Sicily (GSA 16), South Adriatic Sea (GSA18) and North Ionian Sea (GSA19).

Key words

GIS, kriging, Mediterranean Sea, Merluccius merluccius ,nursery areas, spatial analysis, persistence.

1. Introduction

Identification and mapping of habitats essential for completing a resource's life cycle—such as feeding, spawning and nursery areas—represent one of the most important issues in the recent debate on fisheries management (Benaka, 1999; Stoner, 2003; Beck *et al.,* 2003; DeLong and Collie, 2004; Valavanis, 2008). Spatial and temporal information is vital for the development of effective strategies for sustainable resource exploitation (Halliday, 1988; Polacheck, 1990; Caddy, 1999; Lleonart *et al.*, 2003; Berkeley *et al.*, 2004).

Recruitment is one of the key processes regulating fish-population dynamics. Through effects on the survival of larvae or recruits, all the variations in environmental conditions, either natural or human driven, cause high temporal variation of recruit densities over large spatial scales and then have impacts on adult-fish population trends. Fish populations are limited by recruitment at low recruit densities but by density-dependent competition for food resources (White and Caselle, 2008) or cannibalism (Buckley and Livingston, 1997) at high recruit densities.

Recruitment may be described, therefore, as the interplay of high-frequency activating factors (Levin and Pacala, 1997), that is, noisy environmental conditions occurring during early life, and constraining factors acting on juveniles (Bailey *et al.*, 2003). Changes in these constraining conditions result in recruitment variability.

On the other hand, the temporal stability of a density hot-spot of fish juveniles in a given area can be assumed to be indirect evidence of the importance of that area to the recruitment success of the population. In this context, the location of nursery areas would be a precondition for understanding and identifying the environmental factors that control recruitment dynamics and their spatial and temporal scales of influence. In demersal species whose life cycle starts with a pelagic stage, the location of nursery areas is also important to highlight the dependence of spawning and juvenile settlement on key environmental factors such as winds and currents (Hinckley *et al.*, 2001).

Although the protection of nursery areas is worldwide considered a fundamental tool for a proper assessment and management of fishery resources, the temporal persistence of the characteristics of nursery areas would be a fundamental prerequisite for its inclusion in a conservation network but is often not considered.

In the Mediterranean, a recent Council Regulation of the European Community (EC reg. n. 1967/2006) calls for the protection of juvenile-aggregation areas as an important strategy towards a sustainable exploitation of fishery resources. The regulation holds the potential to yield important conservation benefits (Horwood *et al.,* 1998; Gillanders *et al.,* 2003; Mumby *et al.,* 2004) and is based on two assumptions:

- *fish juveniles are particularly vulnerable to fine-mesh trawling (Caddy, 1993; Lleonart and Maynou, 2003) especially when they concentrate in nursery habitats; and*
- *a reduction of fishing mortality on immature fish represents a fundamental prerequisite for sustainable fisheries (Beverton & Holt, 1957).*

In Italy, although sensitive habitats and nurseries located in shallower waters (down to 50 m depth, or within three miles from the coast) are closed year-round to trawling, the juvenile habitats of species such as European hake (*Merluccius merluccius* Linnaeus, 1758) mainly occur off-shore where they are highly vulnerable to legal trawling (Orsi Relini *et al.*, 2002). Despite the recognised importance of protecting hake recruitment from overexploitation, most of the scientific information on its nurseries still tends to be lacking because they are limited to small areas or short duration (Orsi Relini *et al.*, 1986; Ardizzone and Corsi, 1997; Lembo *et al.*, 2000; Belcari *et al.*, 2001; Abella *et al.*, 2005; Murenu *et al.*, 2007; Carlucci *et al.*, 2009). Moreover, due to the different methods and criteria used to detect their location (Beck *et al.,* 2001; Gonî *et al.*, 2004), results are not comparable between areas.

Because of the importance of evaluating the persistence of nurseries to adopt management measures based on area closures, Fiorentino *et al.* (2003) and Colloca *et al.* (2009) studied the time persistence of the recruit occupancy of sea-beds and identified the main nurseries of hake as those areas in which young of the year showed the highest stable densities over time.

The General Fisheries Commission for the Mediterranean (GFCM) manages fisheries regionally through geographical sub-areas (GSAs). Thirty of these were established in 2001 (FAO, 2001) and their boundaries redefined in 2007 (FAO, 2007). Italian waters include seven of the 21 GSAs belonging to the Western and Central Mediterranean sub-areas (Figure1) and extending to 37.5% of that area (22.3% of the whole Mediterranean). Since the 1990s, two main research projects—Gruppo Nazionale Risorse Demersali (GRUND) and Mediterranean International Trawl Surveys (MEDITS)—used annual experimental trawl surveys to evaluate the status of demersal fish resources in Italian waters. GRUND is a national project always carried out in autumn, MEDITS, an international project on which all the EU Mediterranean countries are involved, occur during late spring–summer.

The primary objective of this work was to use geo-spatial methods with trawl survey data to identify hake-recruit aggregation areas. Our paper attempts to define the geographical boundaries of the nursery areas along Italian seas, and to check nurseries stability over time at GFCM-GSA level.

2. Material and methods

In the Italian seas, experimental bottom-trawl surveys have been carried out since 1994 during spring (MEDITS project) and autumn (GRUND project) at depths of 10–800 m. They aimed to obtain estimates of abundance indices and length–frequency distributions for the most important demersal target species (projects details can be found in Relini, 2000; Bertand *et al.*, 2002). Both programs adopt a stratified random sampling design with allocation of hauls proportional to depth-strata extension (10–50 m, 51–100 m, 101–200 m, 201–500 m and 501–800 m).

We analyzed juvenile hake density data (number per square kilometre; n km^{-2}) gathered from the MEDITS and GRUND surveys during 1994–2006 for Italian GSAs.

2.1 Threshold size of recruits

Length–frequency distributions (LFDs) from surveys were standardised by area (km^2) and processed in order to identify the first modal component, which was assigned to the recruits (0^+ age group). LFDs were analyzed using the Bhattacharya method (1967), as implemented in the routine modal progression analysis (MPA) in FISAT II (Gayanilo *et al.,* 2006).

A putative age for the first component was assigned by comparing the estimated length with 14.5 cm total length (TL) that was used as the threshold length at the end of the 1st year of life (Fiorentino *et al.,* 2003). The first component was identified in terms of average length, corresponding standard deviation and number of individuals. Once the cohort's features were identified, the cut-off to isolate recruits was calculated. Hence, recruits-per-haul were estimated as all individuals whose TL was less than the average length + 1 standard deviation.

In GSA 9, the recruit threshold size was established at 14 cm length, based on evidence of a recent study that analysed long-time-series (1985–2004) trawl-survey data on hake recruitment in relation to environmental factors and depth preferences of juvenile hake (Bartolino, *et al.*, 2008).

2.2 Geo-spatial methods

The relevant spatial and temporal dimensions of European hake nurseries have been obtained by modelling the spatial pattern along Italian waters using geo-statistic techniques initially developed for geological and mining resources (Matheron, 1969). These are widely used now to characterize marine ecosystems (Dayton *et al.*, 2000; Ciannelli *et al.*, 2004), and especially to depict the spatial structure of fish populations in Mediterranean (Petitgas, 1993; Fariña *et al.*, 1994; Maynou *et al.*, 2003; Lembo *et al.*, 1998, 1999, 2000; Ardizzone and Corsi, 1997; Fiorentino *et al.*, 2003) and other seas (Vignaux, 1996; Eastwood *et al.*, 2003; Eastwood and Meaden, 2004; Rueda and Defeo, 2003, Woillez *et al.*, 2007).

Based on the regionalized variable theory (Matheron, 1970; Isaaks and Srivastava, 1989), geo-statistic techniques use spatial-interpolation procedures to obtain spatially continuous variables from isolated-station measurements. In this study we refer to one of the most widely used among these procedures (Webster and Oliver, 2001), namely kriging. The spatial correlation was characterized through the use of a semivariogram model (empirical semivariogram), which provided a measure of variance of differences as a function of distance between the observation points or ‘‘lag’’.

Once the semivariogram function was computed from the values sampled at different locations, the weighted least-squares method (Cressie, 1985) was used to best fit theoretical models to empirical semivariograms. Hence, depending on the data, different theoretical model types and variogram parameters (nugget, range and sill) were adapted to reflect the experimental variogram. The selection of these parameters depends on the dimensionality of the problem as well as the number of sample points used to construct the kriging model. Cross validation by the jack-knife technique (Miller, 1974) was used to select the model best describing the spatial continuity.

The best theoretical variogram selected was then used in ordinary kriging to estimate recruit abundance on a regular grid of 0.5 x 0.5 km^2 resolution. A minimum threshold value of observed individuals per unit area was adopted to establish fish density levels adequate to represent the nursery areas, for comparing recruit abundance by survey and GSAs. We adopted the 75th percentile on the cumulative density distribution of recruits.

Ordinary kriging was preferred among the several variants of kriging techniques because it is an exact interpolator that assumes intrinsic stationarity with an unknown but constant mean of the random target-variable (recruit density), which is the case in our study.

Anisotropy was not investigated. The dimensions and shapes of the study areas were inappropriate, and the variogram directional estimates lacked robustness because of the lack of data.

After the estimation of recruit abundance, indicator kriging was used to pinpoint the sites where recruit densities exceeded, at a given probability (75%), the threshold values. Density of recruits was considered a continuous variable that may take all values from zero to some unknown maximum, consistent with the principle of indicator kriging (Journel, 1983; Goovaerts, 1997). We created a new binary variable (I), such that the data are coded zero if they lie below the given critical threshold values (Z_k), or 1 if they lie above it:

$$I(u;Z_k) = \begin{cases} 1 & Z(u) \le Z_k \\ 0 & otherwise \end{cases} \tag{1}$$

The expected value of $I(u;Z_k)$ conditional on n surrounding data, can be expressed as the conditional distribution function at the threshold Z_k and at the location u_0 (Goovaerts, 1997). That probability can thus be derived as a linear combination of indicator data by simple kriging in the usual way (Deutsch and Journel, 1992; Goovaerts, 1994).

Hence, indicator kriging is an interpolation technique which is based on an estimator that is defined as:

$$I^*(u_0;z_k) = \sum_{i-1}^{n} \lambda_i (z_k) I(u_j;z_k) \tag{2}$$

where $I(u_j;z_k)$ represents the values of the indicator at the measured locations u_j, j=1,2,….,n; and λ_i is a weighting factor of $I(u_j;z_k)$ used in estimating $I^*(u_0;z_k)$. These areas with the highest concentration of recruits by year were classified as "main nursery areas".

The resulting maps were then analysed with spatial tools to highlight the consistency of the spatial pattern over time. To evaluate their temporal stability a local persistence index (PI) was adopted. Specifically, a series of at least four consecutive raster features, coming from the probability maps by year (1/3 of the survey time-scale), were combined by applying a local function that computes the mean of the values on a cell-by-cell basis between inputs. In the resulting thematic map of the local persistence index, each cell value is the mean probability (mean PI) with which it belongs to a nursery area. Mean PI ranges from 0, which indicates nurseries are never present, to a maximum value of 1, which indicates areas steadily occupied by nurseries. Areas in which the mean PI exceeded 0.6 were considered “persistent” nurseries.

All spatial analyses were carried out using GeoR (Ribeiro and Diggle, 2001) and Isatis 6.04 for variography, and Arcgis 9.2 (ESRI) for grid rendering and map production.

3. Results

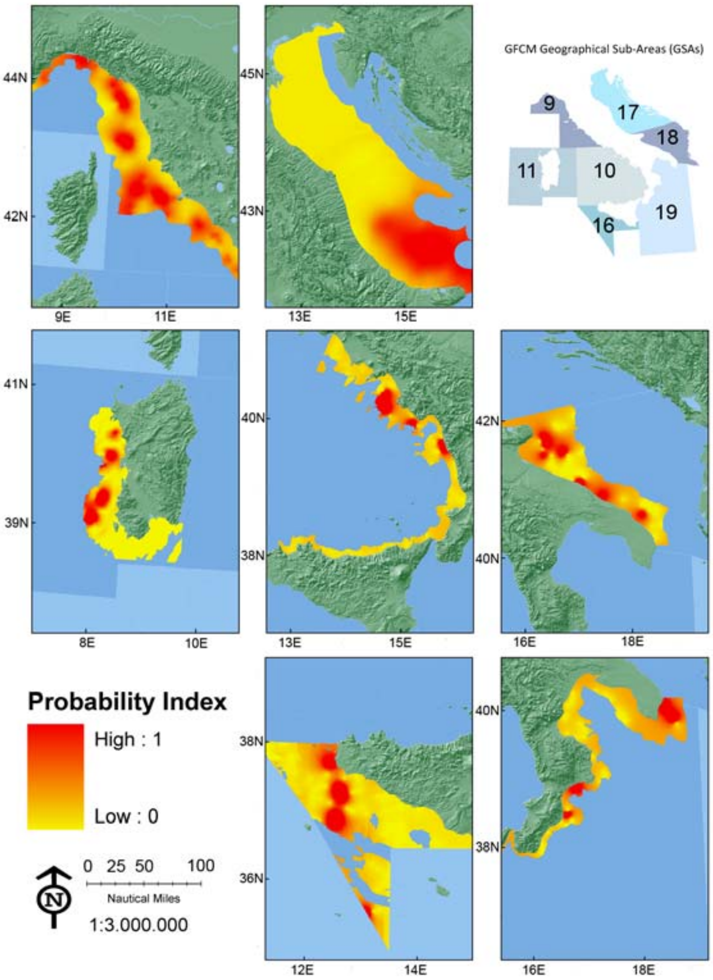
The Bhattacharya analysis of LFDs by mean size of the first modal component highlights a considerable homogeneity in its cut-off size (overall mean = 13.1; CV = 0.14) (Table 1). Overall, the cut-off size from the MEDITS was 1.5 cm lower than from GRUND surveys. Considering that in two GSAs (9 and 17) a fixed cut-off size was used, the highest variability (CV = 0.16) over the years was detected in the MEDITS surveys (GSA11) while the lowest (CV = 0.07) was always observed in the GRUND series (GSA 10, 11 and 19).

Table 1. Estimated length cut-offs (mean length plus 1 standard deviation; in cm) of the 0+ age class of *Merluccius merluccius* by geographical sub-area (GSA) and survey (GRUND—Gruppo Nazionale Risorse Demersali; and MEDIT—Mediterranean international trawl surveys).

	GSA 9[a]		GSA 10		GSA 11		GSA 16	
year/survey	GRUND	MEDIT	GRUND	MEDIT	GRUND	MEDIT	GRUND	MEDIT
1994	14.0	14.0	14.3	12.0	13.1	15.7	11.9	11.2
1995	14.0	14.0	14.6	13.0	13.9	15.2	15.1	13.7
1996	14.0	14.0	14.0	13.0	14.4	15.8	9.5	8.9
1997	14.0	14.0	16.2	14.0	14.0	10.8	14.0	12.5
1998	14.0	14.0	13.4	13.5	13.3	13.3	10.7	11.4
1999		14.0		10.0		9.4		12.8
2000	14.0	14.0	13.7	11.0	15.6	10.8	10.8	11.9
2001	14.0	14.0	14.8	11.5	15.2	11.1	13.7	8.9
2002	14.0	14.0	13.1	11.0	12.2	12.3	10.4	12.2
2003	14.0	14.0	15.2	14.5	14.7	13.0	12.0	11.9
2004	14.0	14.0	14.3	11.0	14.8	13.1	13.1	11.3
2005	14.0	14.0	12.6	13.0	14.7	11.5		
2006	14.0	14.0				11.4		
mean			14.2	12.3	14.2	12.6	12.1	11.5
CV			0.07	0.11	0.07	0.16	0.15	0.13

[a] fixed cut-off size [b] fixed cut-off are not included

Map1 shows probability distribution derived from indicator kriging, that recruit density index exceeded the conditioned threshold for a given GSA and year. The maps visualized for each GSA were chosen among the most representative of the mean pattern of each GSA and based on the best geo-statistical model.



Map 1. An example of recruit abundance in General Fisheries Commission for the Mediterranean geographical sub-areas (GSAs—see locator map at top right) in the study area, derived from indicator kriging. The colour scale indicates gradation in the probability index. Examples come from different years of Gruppo Nazionale Risorse Demersali trawl surveys: GSA9 (2001); GSA10 (2002); GSA 11(1998); GSA16 (1997); GSA17 (1995); GSA18 (2003); and GSA19 (2004).

Hake recruits were widely distributed in GSAs 9 and 18, with several extensive patches of high concentrations. Conversely, recruit distribution in GSA 17 was highly conditioned by the presence of suitable deep bottoms in the southern sector of this sub-area. Well-defined high-density patches were observed in GSA 11 off the western coast of Sardinia; in GSA 19 between Otranto and Santa Maria di Leuca and in the Gulf of Squillace; and in the GSA 10 off the coasts of Campania and Calabria. In GSA 16, recruitment areas occurred along the western sector of the Strait of Sicily along the edge of the offshore bank.

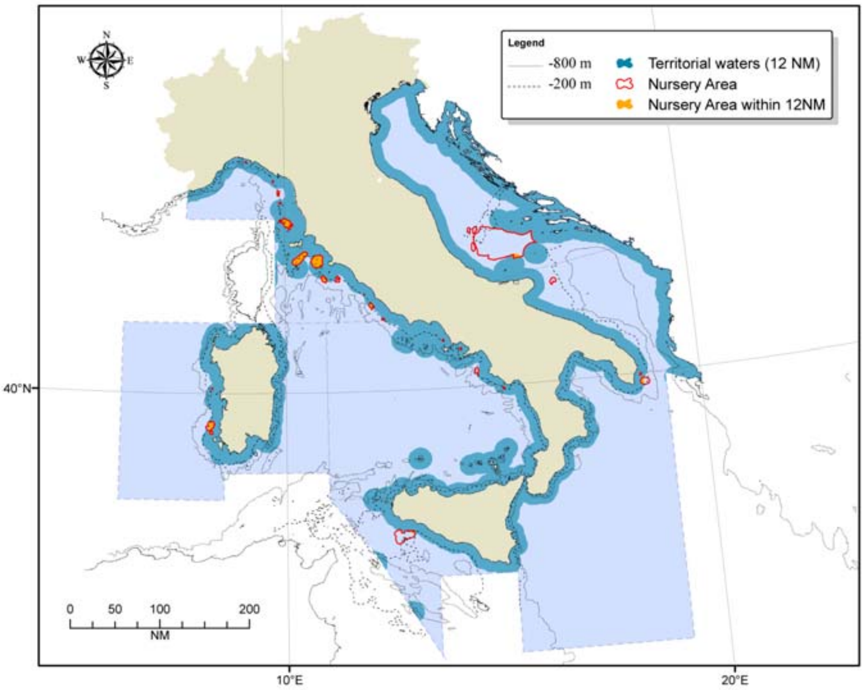
The results of persistence analysis showed a considerable stability in their location. Twenty-three areas with consistently high (PI >= 0.6) recruit densities were identified along the continental shelf break (Map 2, Table 2). Most of these areas were located in the Ligurian and northern Tyrrhenian seas (GSA 9), providing evidence for them to be the area having the strongest recruitment indices. A very extensive nursery was identified in the central Adriatic Sea (GSA 17). Large and persistent nursery areas were located in the Sardinian Sea (GSA 11), the Strait of Sicily (GSA 16) and the Ionian Sea (GSA 19). Small permanent nursery areas were observed in the southern Adriatic (GSA 18) and in the southern Tyrrhenian Sea (GSA 10). Distances of nursery area centroids from the nearest coast ranged from 6 km to 68 km depending on local continental shelf bathymetry gradients.

Table 2. Number and total extension (square kilometres), by geographical sub-area (GSA), of persistent nursery areas for European hake; and relative percentage of these areas outside Italian territorial waters (12 nautical miles).

GSA	number of nurseries	Surface area of nurseries (km²)	% of surface area outside the 12 nm
9	12	1501	17.0
10	4	119	52.0
11	2	277	20.5
16	1	768	90.7
17	1	6177	85.7
18	1	108	100.0
19	2	234	56.4

Map 2. *Recruit persistence index (PI) of Merluccius merluccius in the study area. Red areas indicate where the index exceeds the threshold value of 0.6 for a continuous domain 0–1. Boundaries of General Fisheries Commission for the Mediterranean geographical sub-areas are shown in darker blue. The 200-m depth contour is also shown.*

Table 2 shows the total surface area occupied by the nursery areas identified in each GSA, and the percentage of this area occurring outside territorial waters. A spatial view of this information is provided by Map 3. The smallest surface (about 107 km²) was observed in the southern Adriatic sub-area (GSA 18), whereas the largest (about 6177 km²) was in the central Adriatic (GSA 17) (Table 2). The large nursery area located in the Ligurian and northern Tyrrhenian (GSA 9, about 1500 km²) was, however, fragmented in several patches. Most of the nursery areas were located inside territorial waters, with the notable exception of those of GSAs 16, 17, and 18 (Map 3). In these, the percentage of the recruitment area falling in international waters ranges from 86 % in GSA 17 to 100% in GSA 18 (Table 2).



Map 3. Nursery areas (red outline) within (yellow shading) and outside the Italian territorial waters buffer (12 nautical miles; blue shading).

4. Discussion

This study identified the areas stably occupied by high abundance of hake recruits. Temporal persistence of the ecological characteristics of an area is a pre-requisite for any protection measure based on areas closure (Halliday, 1988; Polacheck, 1990; Caddy 2000; Berkeley *et al.*, 2004). Although different spatial patterns of juvenile hake were observed over the years, results generally showed a considerable stability in high-density areas. Most of the nurseries off the Italian coasts fall within territorial waters, allowing an easy enforcement of management measures. However in three GSAs (16, 17 and 18) a relevant fraction (>86%) of the nursery surface is in international waters. Management in these areas needs an international agreement and actions enforced by international management bodies, such as GFCM, to set up seasonal and/or annual fishery closures.

The identification of “stable” nurseries does not give direct information on the ecological factors that promote the settlement and survival of recruits in these areas. The size, shape and patchiness of the identified fish nursery grounds along the Italian coasts showed large geographic differences, suggesting that the recruitment dynamics varied considerably in relation to either local population abundance or key environmental factors.

As Levin and Pacala (1997) suggested, the survival of larvae, and then the density of future recruits, are strongly influenced by key factors such as temperature and currents. Abella et al. (2008) stated that in the water of Ligurian Sea and Strait of Sicily the position of hake nurseries effectively coincides with zones of relatively higher production, where upwelling and other enrichment processes regularly occur at times. Carlucci *et al*. (2009), related the nurseries in GSAs 18 and 19 to the energetic trophic system driven by the continuous flux of water masses flowing north–south along the western continental shelf of the Southern Adriatic and entering the Northern Ionian Sea. Seasonal changes in nursery location and recruitment strength take place in the Ligurian Sea (Orsi Relini *et al*., 1989; Abella *et al*., 2005) and in the Strait of Sicily (Fiorentino *et al*., 2003), probably due to a reduction in water stratification by Northern Thyrrenian current dynamics. In these areas a weaker late-autumn settlement of hake juveniles occurs in shallower waters, after the most important and deeper spring recruitment. Bartolino, Colloca *et al*. (2008) suggested that temperature at a medium regional scale and wind-driven processes at a local scale, are responsible for hake recruitment variability in the Tyrrhenian. The abundance of recruits is lower in autumn than in summer because temperature plays an important role in survival of larval hake.

The availability of suitable settlement habitats is also an important factor that can explain spatial difference in recruitment patterns. The bathymetric and seabed patterns in the southern boundary of GSA 17 for instance force recruits into the Pomo Pit area because of the absence of other appropriate recruitment habitats. In other areas such as the central-eastern Tyrrhenian and the Ionian seas, the convoluted coastlines and the sea floor morphology (characterized by submarine relief, mud bottoms which are limited in extension, and very narrow and steep shelves and slopes) result in reduced and discontinued habitats for European Hake, hence contributing to increased patchiness in recruit distribution.

We recognize that anisotropy was missing from the present study. The variogram directional estimates lacked robustness in some GSAs due to the lack of data. We have determined to add further data sources and time series, and plan to carry this out in future work. It is anticipated that this further analysis would confirm and strengthen our conclusion about nursery patchiness and recruit distribution.

We also hope that further studies are undertaken at region/basin level to relate the space–time dynamics of recruits to different oceanographic, environmental and anthropic processes, confirming and generalizing the findings from small areas (Fiorentino, 2003; Bartolino *et al.*, 2008; Politou *et al.,* 2008; Tserpes *et al.*, 2008; Carlucci *et al*., 2009).

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