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# A GIS environmental modelling approach to essential fish habitat designation

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**Abstract**

Proper designation of essential fish habitat (EFH) is a highly important spatial measure in any management of fishery resources. EFH is characterised by an aggregation of abiotic and biotic parameters that are suitable for supporting and sustaining fish populations during all stages of their life cycle. We propose a multi-parameter model that includes processing and integration of EFH environmental and biological descriptors under a Geographic Information System. We apply the model to short-finned squid population dynamics in the eastern Mediterranean Sea, based on species life history data derived from biological and genetic research. The model output includes squid monthly EFH designations for the 1997–1998 fishing season and reveals the spatiotemporal aspect of the biological and ecological squid dynamics in the region.



*Keywords:* Fisheries model; Cephalopods; Satellite imagery; Ecological modelling; GIS

## 1. Introduction

In 1996, the renamed US Magnuson–Stevens Act mandated the identification of essential fish habitat (EFH) for 'quota' species. The US Congress defined EFH as 'those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity', a definition that includes the physical, chemical and biological properties of marine areas and the associated sediment and biological assemblages that sustain fish populations throughout their full life cycle (DOC, 1997). Under this Act, the designation of EFH in US waters is based on the best available science regarding the habitat requirements of each species. The compilation of the available information on the distribution, abundance and habitat requirements for each species in EFH reports comprises an extensive survey of the important biological and genetic literature as well as original analyses of

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fishery-independent datasets documented in species life history data reports referred to as the EFH source documents.

Species life history data include information on current and historic stock sizes, stock assessments, geographic range and periods and location of major life history stages. In addition, information on the habitat requirements is provided for each life history stage, including the range of habitat and environmental variables that control or limit distribution, abundance, growth, reproduction, mortality and productivity. Specifically, these data provide information on species type (e.g., benthic or pelagic), species preferred living ranges of temperature and salinity, recruitment periods, spawning periods and characteristics (e.g., preferred spawning sediment types and spawning temperature and depth ranges), migration habits, maximum depth of species occurrence, etc.

Species life history data may be viewed as the starting point for spatial analysis and modelling of EFH through new technologies such as Geographic Information Systems (GIS) and Remote Sensing (RS). GIS may use species life history data as constraint parameters in the analysis of remotely sensed environmental and surveyed fisheries data, providing integrated output on seasonal areas that are important in various stages of species life cycles. GIS may reveal the geographic distribution of species life history and, in combination with results from RS-based oceanographic GIS analysis, may reveal the dynamic interactions between species populations and oceanographic features in a spatiotemporal scale (Meaden, 2000; Valavanis, 2002). Specific spatial and temporal patterns on species resources dynamics (e.g., spawning and aggregation locations and abundance geodistribution) may be examined with the use of GIS.

Several studies are focused to this end. Marine species population spatiotemporal dynamics are studied through GIS and associated RS, surveyed and life history data for the mapping of spawning grounds for sardine and anchovy (Lluch-Belda et al., 1991), walleye pollock (Varkentin et al., 1999), herring (Brown and Norcross, 1999), sole (Eastwood et al., 2001), salmon (Geist and Dauble, 1998), squid (Kiyofuji et al., 1998; Roberts, 1998; Waluda and Pierce, 1998; Xavier et al., 1999; Sakurai et al., 2000; Bellido et al., 2001) and cuttlefish (Pierce et al., 1998; Denis et al., 2001; Valavanis et al., 2002). Additionally, the distribution of optimum living habitat is modelled through GIS for tiger prawn (Loneragan et al., 1998), sardine, anchovy and hake (Yanez et al., 1996; Logerwell and Smith, 1999), weathervane scallop (Turk, 1999) and lesser sandeel (Wright et al., 2000). A NOAA website (http://www.fakr.noaa.gov/maps) simplifies the process for making informed decisions for species EFH by using both spatial and tabular data over the Internet. Here various geographic information and tabular datasets derived from fisheries catch and observer data and known science are organised under an online GIS environment, which pulls the spatial and tabular data together providing an easy and powerful tool for the designation and management of EFH in the Alaskan region.

Guisan and Zimmermann (2000) reviewed the modelling efforts used for the prediction of species habitat distribution. Most approaches use ordinary multiple regression (e.g., Generalized Linear Models), neural networks, ordination and classification methods, Bayesian models, locally weighted approaches (e.g., Generalized Additive Models) or combinations of these models. Koutsoubas et al. (1999) developed a GIS on cephalopod resource dynamics in the eastern Mediterranean, an application that is based on the integration of species life history data and environmental variables that describe certain oceanic processes (upwelling, gyres and fronts). Arvanitidis et al. (2002) overviewed the biology of the short-finned squid in the NE Atlantic and Mediterranean in terms of species–environment–habitat interactions while Georgakarakos et al. (2002) developed a model for the prediction of loliginid and ommastrephid squid stocks in the eastern Mediterranean based on univariate and multivariate time series analysis of environmental and habitat descriptors. Finally, benthic habitat data and suitability indices of relative abundance across environmental gradients are commonly used within GIS in order to develop Habitat Suitability Index (HSI) models (e.g., Christensen et al., 1997; Rubec et al., 1998a,b; Brown et al., 2000). HSI models may help predict optimal habitat and abundance zones for various species, therefore aiding managers in designating EFH.

With the rise of new powerful statistical techniques and GIS tools, the development of predictive habitat distribution models has rapidly increased in ecology (Guisan and Zimmermann, 2000). Such models are static and probabilistic in nature, since they statistically relate the geographical distribution of species to their present environment. Here, we propose a GIS EFH model that is based on the spatial integration among vector and raster datasets, including satellite imagery on sea surface temperature distribution and chlorophyll concentration, surveyed sea surface salinity distribution, monitored fisheries production and fishing fleet activity data and bathymetry. Integrations among these EFH descriptors are constrained by species life history data on optimum (or preferred) living conditions and maximum depth of species occurrence. The model is applied to short-finned squid, *Illex coindetti* Verany, 1839 (Cephalopoda, Omnastrephidae) population dynamics in the eastern Mediterranean Sea during the 1997–1998 fishing season, revealing the spatiotemporal distribution of species EFH on a monthly basis.

## 2. Study site, data and model description

The study area includes the Hellenic Seas (Eastern Mediterranean) comprising four main water bodies, the Aegean and Ionian Seas and the north parts of the Libyan and Levantine Seas (Fig. 1). The topography of the area is characterised by extreme changes in bathymetry, featuring extensive and smaller shallow continental shelves (North Aegean and Cyclades plateau and Cretan continental shelf) interrupted by deep trenches (North Aegean trough and Chios and Cretan basins). The area is well monitored in terms of monthly satellite imagery and fisheries data (Table 1). Sea surface temperature distribution (SST) is available through the German Aerospace Agency's (DLR) satellite data archive while sea surface chlorophyll concentration (Chl-a) is available through NASA's Distributed Active Archive Center. Sea surface salinity

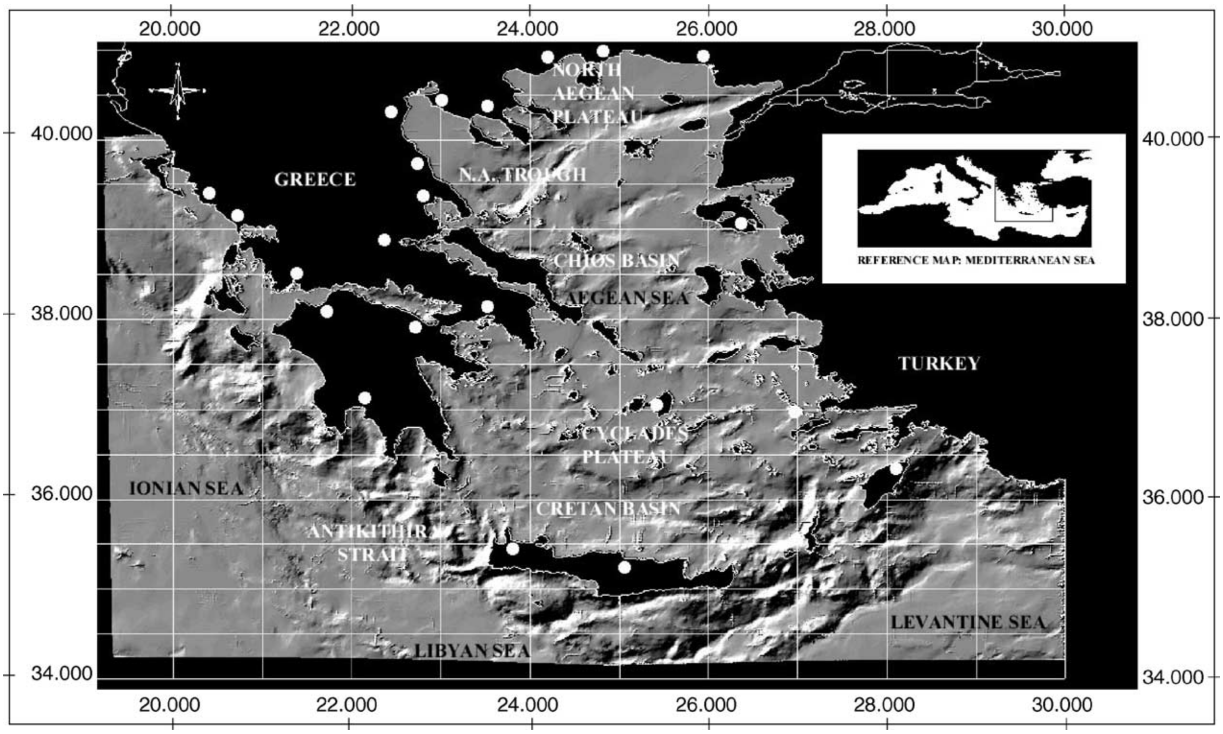


Fig. 1. The study area is located in the eastern Mediterranean Sea. This bathymetry image shows the Aegean Sea and part of the Ionian, Libyan and Levantine Seas revealing extreme changes in the topography of the region (North Aegean Plateau and trough, Chios Basin, Cyclades Plateau and Cretan Basin). Major fishing fleet activity occurs on the North Aegean and Cyclades Plateau and in the Antikithira Strait. Official fisheries data sampling stations and fisheries production statistical rectangles are also shown.

Table 1
Data variables and their characteristics used for the initiation of the GIS-based EFH model

| Data variable | Sensor sampler | Spatiotemporal resolution | Data type | Archive source |
|---|---|---|---|---|
| Sea surface temperature (SST) | Advanced very high resolution radiometer (AVHRR) | 1.6 km, monthly, May 1993–December 2000 | RASTER | German Aerospace Agency (DLR) |
| Sea surface chlorophyll (Chl-a) | Sea viewing wide field of view sensor (SeaWiFS) | 4 km, monthly, September 1997–December 2000 | RASTER | Distributed Active Archive Center (NASA) |
| Sea surface salinity (SSS) | Processed historical in situ measurements | 10 km, monthly, decadal climatology | RASTER | Mediterranean Oceanic Database (MODB) |
| Fisheries production (catch) | Monitored data through official sampling stations | 60 km × 40 km rectangles, monthly, January 1995–December 2000 | VECTOR | Hellenic Fisheries Management System (HFMS) |
| Fishing fleet activity areas | Monitored data through official sampling stations | 1:100,000, yearly, 1996–2000 | VECTOR | Hellenic Fisheries Management System (HFMS) |
| Bathymetry | Processed ERS-1, Geostat and historical depth soundings | Raw data: 10 km, processed data: 50 m isobaths | VECTOR | Laboratory for Satellite Altimetry (NOAA) |
| Coastline | Digitisation of nautical charts and aerial photography | 1:100,000 | VECTOR | Hellenic Ministry of Environment |
| Species life history data | Literature research | N/A | ASCII TEXT | CEPHBASE and ICES |

Species life history data refers to short-finned squid (*Illex coindetti*) life cycle in Atlantic Ocean and Mediterranean Sea.

distribution (SSS) is available through the Mediterranean Oceanic Database as a decadal climatological product (Brasseur et al., 1996). Monthly fisheries production and fishing activity data are officially sampled through a network of 22 sampling stations operated by the Hellenic Centre of Marine Research through the Hellenic Fisheries Management System (HFMS). Coastline is derived through digitisation of aerial photography and nautical maps while bathymetry is calculated through processing (kriging) of a point dataset derived from a blending of depth soundings collected from ships with detailed gravity anomaly information obtained from the Geosat and ERS-1 satellite altimetry missions (Smith and Sandwell, 1997). Species life history data (Table 2) on short-finned squid population dynamics are derived from biological and genetic studies (Boyle, 1983; Raya et al., 1995), CEPHBASE (Wood et al., 2000) and official reports (Anon. 1996, 1997). All datasets are commonly georeferenced and organised under a GIS environment in regular grids and vector coverages of polygon topology (Valavanis et al., 1998).

The proposed EFH model is based on spatial data integrations using the Environmental Systems Research Institute's ARC/INFO GIS (ESRI, 1994). The model is linked to a GIS database and it performs extensive

Table 2
Example of species life history data on the ecology and biology of four cephalopod species in NE Atlantic, organised and provided by the International Council for the Exploitation of the Sea (ICES)

| Species life history | Long-finned squid (*Loligo vulgaris*) | Cuttlefish (*Sepia officinalis*) | Common octopus (*Octopus vulgaris*) | Short-finned squid (*Illex coindetti*) |
|---|---|---|---|---|
| Benthic/pelagic | Pelagic | Benthic | Benthic | Pelagic |
| Temperature range | 10–25 °C | 10–30 °C | 10–30 °C | 7.5–20 °C |
| Spawn season | December–January | March–July | June–September | Spring/fall |
| Spawn depth | 10–30 m | 2–50 m | 100 m | Unknown |
| Substrate type | Hard | Muds/sands | Rocks/sands | Unknown |
| Bathymetry range | 10–100 m | 10–300 m | 0–500 m | 60–350 m |
| Migration pattern | In > offshore | Off > inshore | Off > inshore | Unknown |
| Migration scale | 200 km | 50 km | 50 km | Unknown |

Life history information on short-finned squid preferred temperature and bathymetry ranges were used as guide in data integrations through the proposed EFH model.

Table 3
List of GIS integrations performed by the proposed EFH model among vector and raster datasets constrained by species life history data for the modelling of *Illex coindetti* EFH

| Integration datasets | GIS analysis type model module | Model result |
|---|---|---|
| 1. Species total catch coverage (statistical rectangle system) | Selection for species catch more than 0 kg (stage A) | Geodistribution of species catch |
| 2a. Geodistribution of species catch 2b. Species maximum depth of occurrence (bathymetric dataset and species life history data) | Spatial integration between polygon coverages (stage A) | Geodistribution of species major occurrence areas |
| 3a. Geodistribution of species major occurrence areas 3b. Fishing fleet major activity areas | Spatial integration between polygon coverages (stage A) | Geodistribution of species major concentration areas |
| 4a. Geodistribution of species major concentration areas 4b. Monthly SST, Chl-a, SSS | Spatial selection between a polygon coverage (vector) and monthly grids (raster) (stage B) | Minimum and maximum values of species SST, Chl-a, SSS preferences |
| 5a. Minimum and maximum values of species SST, Chl-a, SSS preferences per month 5b. SST, Chl-a, SSS monthly grids | Spatial selection in grids using certain minimum and maximum values and conversion of selected areas to polygons (stage C) | Species preferred areas based on SST, Chl-a, SSS minimum and maximum values |
| *Final integration:* 6a. Species preferred areas based on SST, 6b. species preferred areas based on Chl-a, 6c. species preferred areas based on SSS | Spatial integration among polygon coverages (stage D) | Modelled monthly EFH based on optimum habitat environmental descriptors |

data integration analyses and modelling among vector and raster datasets (Table 3). EFH modelling is developed for short-finned squid populations in the eastern Mediterranean for the period September 1997–August 1998. The EFH model consists of four main analytical stages (Fig. 2):

1. *Stage A (species concentration areas):* Monitored fisheries production (catch data) and bathymetry (maximum depth of species occurrence) are spatially integrated to reveal species major occurrence areas. The resultant dataset is spatially integrated with fishing fleet activity data to reveal species major concentration areas. All integrations are performed on vector datasets (spatial integration among polygons).
2. *Stage B (environmental integration):* The resultant dataset from stage A (species major concentration areas) is separately integrated with SST, Chl-a and SSS (spatial integration among a regular grid and a polygon coverage). Minimum and maximum values in these three EFH environmental descriptors are calculated.
3. *Stage C (environmental selection):* The resulted minimum and maximum values from stage B are applied to satellite imagery for SST and Chl-a and surveyed salinity dataset in order to reveal areas that satisfy the derived minimum and maximum environmental values. This spatial selection in regular grids results in three grids that show areas describing EFH in terms of SST, Chl-a and SSS.
4. *Stage D (EFH output):* The three output grids from stage C are converted to polygon coverages. The three vector coverages are integrated into one polygon coverage that describes those areas that commonly satisfy species preferred living conditions in terms of optimum SST, Chl-a and SSS values (modelled EFH, spatial integration among polygons).

## 3. Results and discussion

The organisation and manipulation of fishery data through GIS provides new approaches for further data processing. The integration of monitored fishery catch data with bathymetry reveals ‘species major occurrence areas.’ Such spatial integration is constrained by life history data on maximum depth of species occurrence. In the case of *Ofillex coindetti*, we use a depth limit of 350 m. This limit is critical mainly for

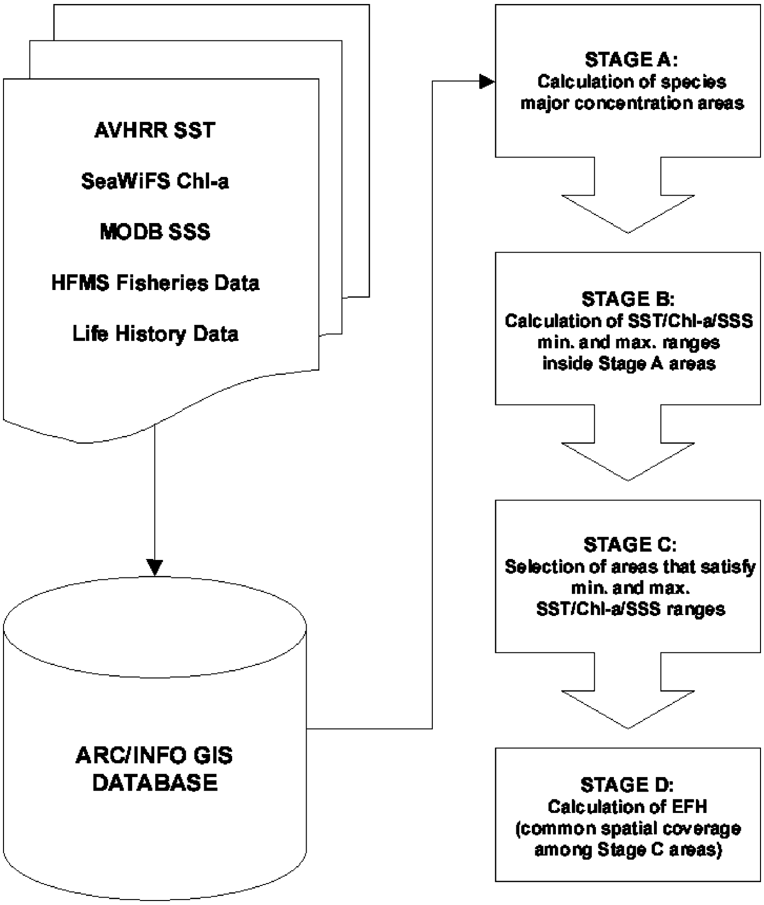


Fig. 2. Architecture of the GIS EFH model. Four main data analysis and modelling stages are linked to a GIS database where remotely sensed and monitored data, derived from international and national online data archives, are stored. The EFH modelling is a series of spatial integrations among raster and vector datasets for the spatiotemporal mapping of species optimum living conditions in terms of SST, Chl-a, SSS and bathymetry.

two reasons: First, the depth of 350 m is the limit *Forillex coindetti* occurrence (based on the species life history). Second, the same limit represents the average depth of the major fishing tool targeting on *Illex* in the area (trawl). In addition, most of the fishery grounds, where the commercial fishing fleet operates in the study area, are found below the 350 m bathymetric contour (Fig. 1). The resulted 'species major occurrence areas' are integrated with fishing fleet major activity areas to reveal 'species major concentration areas' (Fig. 3). We assume here that 'species major concentration areas' describe *Illex*-favoured habitat in a more realistic way than the areas included in the initial fisheries catch-monitoring grid (60 km × 40 km sampling 'rectangles' shown in Fig. 1). Thus, smaller 'species major concentration areas' allow extraction and calculation of environmental ranges that may be considered as more compact and robust environmental descriptors of species habitat.

These data manipulations (stage A of the EFH model) are highly important for the extraction of habitat environmental descriptors and the final EFH modelling through the rest of the model's stages. The output on 'species major concentration areas' is used as the basic spatial extent for the selection of those environmental ranges that species prefer as their optimum living habitat. In this integration between vector and raster datasets, minimum and

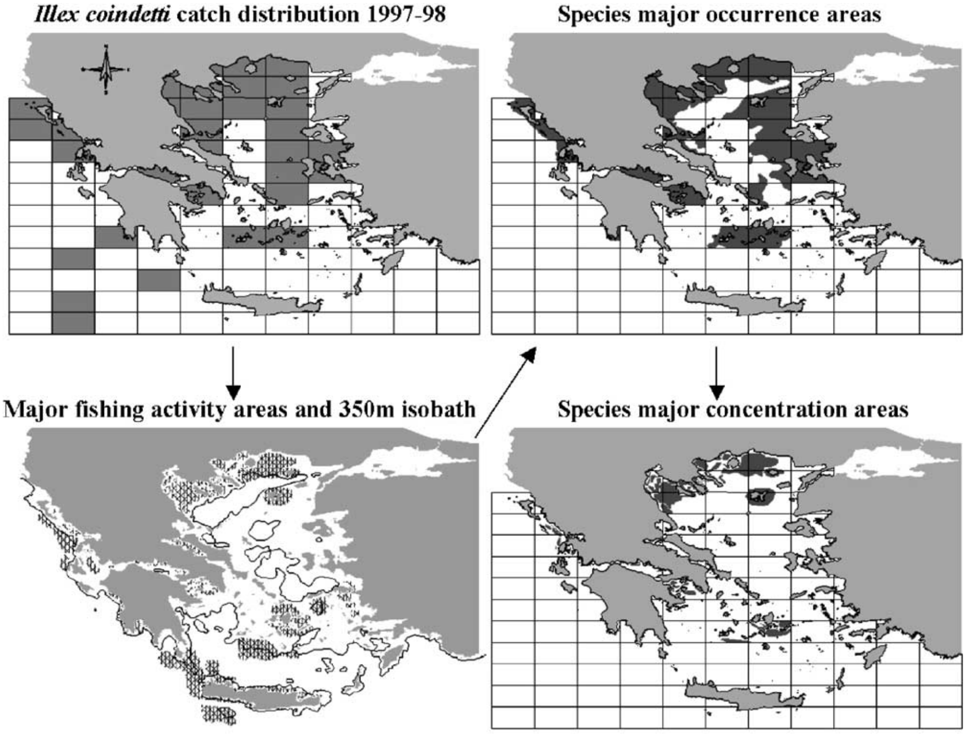


Fig. 3. Spatial integrations among georeferenced fishery data (EFH model: stage A). Catch distribution (top left) is integrated with bathymetry (bottom left) to reveal species major occurrence areas (top right), which in turn, is integrated with fishing fleet major activity areas (bottom left) to reveal species major concentration areas (bottom right). Species concentration areas are used for the extraction of minimum and maximum SST, Chl-a and SSS ranges that are important for the modelling of the species EFH.

maximum environmental descriptors are calculated for SST, Chl-a and SSS. Finally, the combined selection through spatial integration of SST, Chl-a and SSS minimum and maximum values reveals those regions that commonly characterise species preferred living environmental conditions (EFH). Fig. 4 shows the final output of the EFH model, which includes modelled monthly EFH for *Illex coindetti* during 1997–1998.

From a biological perspective, the resulted GIS modelling of short-finned squid EFH in the eastern Mediterranean reveals the spatiotemporal distribution of the species life history information on habitat preferences and migration habits (Fig. 4). During summer months (June–August, not presented here), trawling activity is officially prohibited throughout the study area. The fact that no major areas of EFH are found during this period (although summer data were included in the EFH model) may be connected to species decreased growth rate from a limited food supply (Amaratunga et al., 1980) and species post-spawning high mortality (Roper et al., 1984). During fall and winter months, species growth rate increases and as a highly mobile and opportunistic species, short-finned squids migrate offshore to take advantage of upwelling regions and associated plankton blooms (Boyle, 1983; Valavanis et al., 2002). Winter offshore upwelling events in the study area occur at locations around Antikithira Strait and south of Crete Island (Valavanis et al., 1999), mainly due to seasonal strong winds and associated gyres in the region (Theocharis et al., 1993). During spring months with spring spawning season approaching, species start their spawning migration in a southward direction (Amaratunga, 1981; Dawe et al., 1981; Rathjen, 1981) to find warmer spawning and egg development temperature ranges (Boletzky et al., 1973). A comparison between temperature ranges preferred by NE Atlantic (Table 2: 7.5–20 °C, ICES data) and

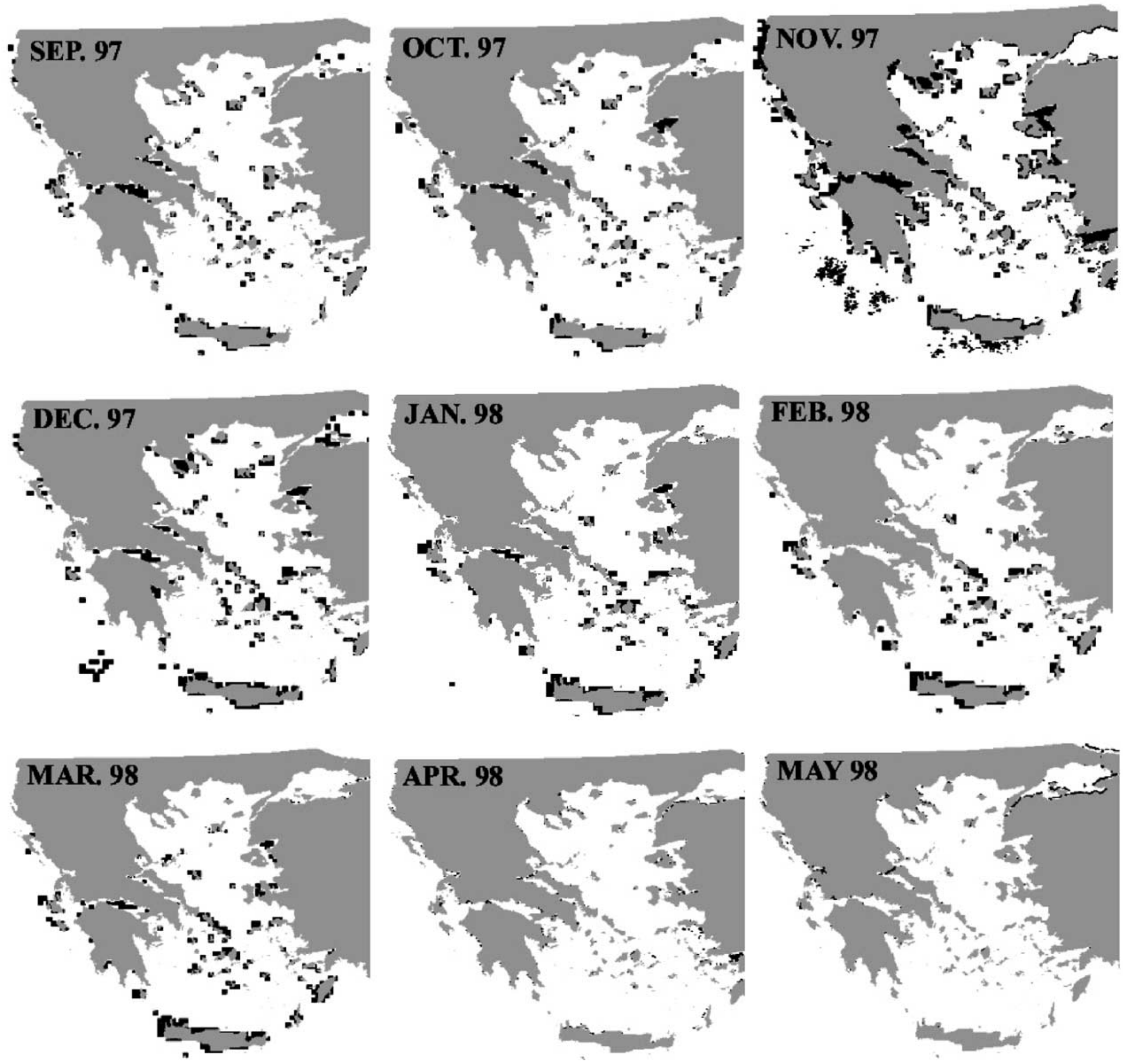


Fig. 4. Modelled EFH for short-finned squid population dynamics in the eastern Mediterranean during the fishing season starting fall 1997 and ending spring 1998 (EFH model: stage D). EFH areas (in black) commonly satisfy species-preferred or optimum living ranges in four EFH environmental descriptors (SST, Chl-a, SSS and bathymetry). Model stage C-derived environmental values that characterise these areas are: MinSST: 3 °C, MaxSST: 29 °C, MinChl-a: 0.30 mg/m$^3$, MaxChl-a: 15.60 mg/m$^3$, MinSSS: 36.12‰, MaxSSS: 38.51‰.

Mediterranean (Fig. 4: 3–29 °C, EFH model) squid populations reveals that Mediterranean squids tolerate a wider temperature range, a biological pattern that is well documented (Arkhipkin et al., 2000; Anderson and Rodhouse, 2001; Machias et al., 2001; Arvanitidis et al., 2002; Ragonese et al., 2002).

From a GIS modelling perspective, the use of species life history data on habitat preferences in terms of environmental descriptors, fishery data and bathymetry ranges proved adequate for species EFH simulation. The model allows the constrained integration of various datasets in order to map the spatial extent of species preferred habitat conditions. The organisation of habitat variables, important to species biology and ecology, in a GIS environment allowed the manipulation of the associated georeferenced datasets in order to 'transform' species life history information (document data) to easily interpretable digital maps (spatiotemporal data). This data transformation provides an important tool for the comprehending of species population dynamics and encourages spatial thinking in management efforts through information-based designation of the spatial and temporal extent of EFH. The GIS-based EFH model may be applied to species that are sensitive to certain environmental and topographic features throughout their life cycle. According to the life history data of the targeted species, additional datasets may be introduced in the model in terms of bottom substrate types, underwater vegetation assemblages, dissolved oxygen values, pollutant parameters, etc. The model is selected for inclusion in the Hellenic Fisheries Management System (HFMS), which is an on-going development effort for implementing a Fisheries GIS infrastructure for Hellenic fishery resources management to be concluded by 2006 (GSRT, 2003). Through HFMS, the model will function in both local and regional modes on species-specific or group-of-species modelling applications, since the spatial scale of the model output depends on the resolution of the input datasets while the accuracy of model results depends on the habitat descriptive capability of the input variables.

## 4. Conclusions

A four-stage model for the identification and mapping of essential fish habitat (EFH) is proposed, based on the georeferenced integration of several EFH environmental descriptors under a GIS environment. Parameters that describe EFH are derived from species life history data, which are used as the model's constraint factor. These parameters include satellite imagery on sea surface temperature distribution and chlorophyll concentration, sea surface salinity distribution, fisheries production and fishing fleet activity areas and bathymetry. Integration of these datasets is constraint by life history data on species preferred or optimum environmental conditions and bathymetry ranges. The model output is better suited to reflect theoretical findings on the spatiotemporal nature of the species' response to species-preferred environmental conditions.

The model is applied to short-finned squid population dynamics in the eastern Mediterranean Sea, based on the above parameters, however it may be extended to include more variables depending on the available life history information of the targeted species. The proposed EFH model is a useful tool in fisheries management efforts by contributing as part of GIS-based decision support systems, especially in the identification of species seasonal aggregation regions, the monitoring of the variability of catch in these regions and ultimately, the design of marine protected areas or seasonally closure areas.

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