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DEVELOPMENT OF A MARINE INFORMATION SYSTEM FOR CEPHALOPOD FISHERIES IN EASTERN MEDITERRANEAN

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ABSTRACT

An interfaced marine information system is developed for integrated analysis of fisheries of five commercially important cephalopod species in Greek waters of the Eastern Mediterranean. The system combines data on the spatial and temporal patterns of cephalopod population dynamics focusing on geo-distribution of abundance, environmental variation, fisheries, spawning areas and migration habits. The system is developed as a customisation of a workstation ARC/INFO environment and features a series of innovative GIS map-overlay and integration routines for analysis and modelling of surveyed, statistical, and remote-sensed data. Geo-referenced datasets include cephalopod catch and landings, coastline-bathymetry, bottom substrate types, and a set of environmental variables provided by satellite sensors (AVHRR/sea surface temperature and SeaWiFS/chlorophyll-a concentration) and climatologic datasets (sea surface salinity). The innovative aspect of this marine system is the integration of species life history data to GIS analysis. Species preferences on certain spawning conditions, migration habits, and depth ranges are used as constraints in GIS analysis and integration. The application of GIS and Remote Sensing technologies has proved useful for the mapping of seasonal spatial components of cephalopod population dynamics. Results from this application may be used for information-based species management proposals, which is the goal of further development of this marine information system.

Fishing pressure on marine biota has increased during the last decade. Data from the Food and Agriculture Organization of the United Nations (FAO) reveal no rise in marine catch during this period (Meaden and Do Chi, 1996). FAO statistics on cephalopod catch in the Mediterranean show no rise since 1988 (FAO, 2000). Data from the Greek National Statistical Service (GNSS) reveal the same pattern in cephalopod fisheries in the Eastern Mediterranean since 1994. The need for information as a means of natural resource control and management can be met by the technology of Geographical Information Systems (GIS) as tools for identifying important spatial components of marine species population dynamics. GIS techniques have proved useful for the identification of such components as seasonal geo-distribution of abundance, spawning grounds, areas of concentration, migration corridors, and suitable habitats.

Studies on the biology and fisheries of the cephalopods in general and in particular of those species having a resource potential in the Mediterranean are limited compared with those of the adjacent NE Atlantic waters or other basins and oceans of the world (Pacific, Antarctic). Furthermore, the currently available information on the exploitation and study of the cephalopods in the Mediterranean comes mainly from the western basin while in the eastern basin there is only scattered information on the species exploited (Worms, 1979; Mangold and Boletzky, 1987). In Greek waters, scientific knowledge of the class was scanty till the early 90s and mainly concerned species composition (Kaspiris and Tsiambaos, 1986) or a certain fishing gear (Stergiou, 1988; Stergiou et al., 1997). Since the early 90s, however, the distribution and abundance of cephalopods in the Greek Seas have started to be regularly monitored (D'Onghia et al., 1992; Lefkaditou and Kaspiris, 1996) but the data have not yet been thoroughly analysed.

This work presents a series of innovative marine data integrations using GIS for the identification of those geographic areas that are important to species populations. Currently, very few marine GIS applications integrate species life history information allowing mapping of seasonal characteristics of species populations (Goodchild, 2000; Meaden, 2000). The aim of this work is to demonstrate how innovative GIS techniques can be grouped into one marine GIS tool revealing various spatio-temporal patterns of population dynamics through integration of remotely sensed, surveyed, statistical, and species life history data. Five cephalopod species with resource potential in Greek waters are analysed: *Illex coindetii* Verany, 1839 (short-finned squid), *Loligo vulgaris* Lamarck, 1798 (long-finned squid), *Sepia officinalis* Linnaeus, 1758 (cuttlefish), *Octopus vulgaris* Cuvier, 1797 (common octopus), and *Eledone* spp. (mainly, musky octopus).

Application of GIS techniques to the marine environment is an adaptive process (Goodchild, 2000). A marine GIS development deals with three major marine components, those of marine objects (e.g. species populations), marine processes (e.g., oceanographic fronts, gyres, upwellings, etc.), and the vertical dimension (Meaden, 2000). Marine GIS is called to first study these components (adaptation) and then give meaningful results of spatio-temporal nature for the relations among these components. Also, marine GIS development is a multi-disciplinary procedure. Marine biologists, oceanographers (physical and biological), and GIS developers participate in the various stages of the development process, from optimum database structures (Durand, 1996; Valavanis et al., 1998) and user-interface development (Su, 2000) to final checking of marine GIS output and accuracy.

Materials and Methods

The study area includes the Greek Seas (Eastern Mediterranean), comprising three bodies of water: the Aegean, Ionian, and Cretan Seas. The bathymetry of the area reveals two major plateaux (North Aegean and Cyclades Plateaux). Major fishing activity in the area is concentrated in these plateaux as well as the Antikithira Strait (Fig. 1). Catch data are obtained by official fisheries reporting centers that are dispersed throughout the study area (total 25 stations). Data are organized in a 30×50 km statistical rectangle system. The datasets that are used in the GIS integrations are listed in Table 1. These data are obtained from a variety of sources including publicly available Internet data servers (satellite data) and national data holders (statistical data).

Data are inserted in ESRI's (Environmental Systems Research Institute) ARC/INFO GIS as INFO files, grids, and thematic coverages of various topologies (ESRI, 1992). These GIS datasets are referenced under a common geo-reference system, in this case, Universal Transverse Mercator-units meters (Valavanis et al., 1998). The marine system features a complete user-interface, which consists of a hierarchy of selection and integration menus that call specific GIS routines. The programming language is ESRI's AML (Arc Macro Language) and the operating system is UNIX. The interface allows users to interact with a certain part of the GIS database while performing specific analysis tasks. In addition, the existence of a user-interface in a complex GIS application makes the development usable and user-friendly (ESRI, 1994).

Analytical and integration routines were developed to address specific spatial questions on cephalopod resources dynamics, such as: where do cephalopod species spawn, what are their migration corridors, where are the areas of species occurrence, where are they mainly fished, what is the geo-distribution of their abundance, where are their seasonal suitable habitats, ques-

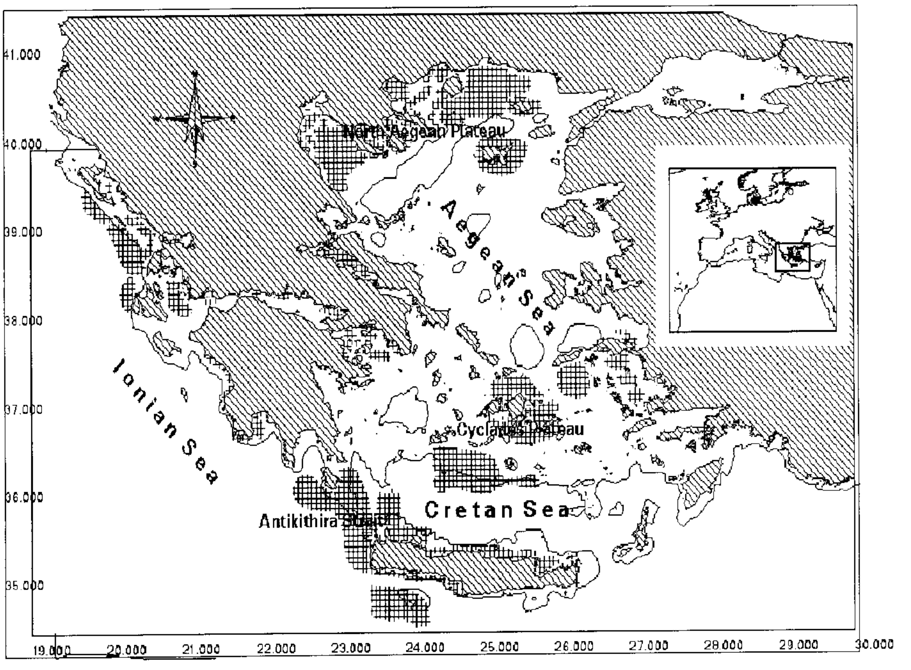

Figure 1. The Greek Seas. Major fishing activity areas and the bathymetric contour of –600 m (boundary of continental shelf) are shown. Fishing areas include the spatial distribution of five fishing tools: trawlers and artisanal, purse- and beach-seiners, and long-liners.

tions including the temporal context. The architecture of the development of the marine GIS tool is presented in Figure 2.

A simple map overlay routine using the coastline and the catch values in each rectangle is used for the mapping of catch distribution. The same technique is applied for the mapping of landings distribution. Predicted species occurrence areas are mapped by spatially integrating coastline-bathymetry and species catch geo-distribution with constraint the species maximum depth of occurrence based on known life history data (Boyle, 1983; ICES, 1996; ICES, 1997; IMBC unpubl. data). Finally, spatially integrating geographic areas of predicted species occurrence and fishing fleet activity revealed species major catch locations.

The mapping of potential spawning grounds required processing and integration of sonar and photography data. Sonar data were obtained during hydroacoustic surveys on board RV Philia, the research vessel of the Institute of Marine Biology of Crete (surveys occurred during winter 1999). Aerial photography was taken by an airplane at an altitude of 1500 m and gave coastal photographs of scale 1:5000 (flights occurred during summer 1999). Sonar data were organised in a thematic coverage of point topology. Aerial photographs were registered and rectified and point sediment-type data were extracted and placed with surveyed sonar point data in a thematic coverage. Interpolation of the set of point values resulted in a grid showing substrate types. The resulted substrate grid was integrated with sea surface temperature imagery (SST) and sea surface salinity (SSS) data as well as bathymetry. Constraints from life history data on species spawning preferences on SST, SSS, bathymetry ranges, and substrate type (Boyle, 1983; ICES, 1996; ICES, 1997; IMBC unpublished data) were applied in the spatial integrations to reveal potential species spawning grounds.

The study of relations between species catch geo-distribution and various environmental datasets such as SST, SSS, and Chlorophyll-a (Chl-a) was approached in two ways: First, a classification of surface waters based on their values of SST, SSS, and Chl-a was performed. Three average grids of

Table 1. List of datasets included in the GIS database and their sources.

1. Environment	
Advanced Very-High Resolution Radiometer (AVHRR), Sea Surface Temperature (SST), 1993-present monthly German Aerospace Agency imagery, 1.6 × 1.6 km	http://www.dlr.de/
Sea Surface Salinity, 1980-89 climatologic dataset, 25 × 25 km, Mediterranean Oceanic Database	http://modb.oce.ulg.ac.be/
Sea Wide Field-of-view Sensor (SeaWiFS), Sea Surface Chlorophyll-a Concentration (Chl-a), 1997-present monthly imagery, 10 × 10 km	http://seawifs.nasa.gov/
RoxAnn® substrate types and aerial photography for bottom sediment mapping	IMBC National Projects
Coastline/Bathymetry, Scale 1:250.000	Greek Military Hydrographic Service
2. BIOLOGY/STATISTICS	
Genetic and biological data	IMBC Partnership in EC Project
Species life history data	Boyle, 1993, Annual Reports of ICES Working Group on Cephalopod Fisheries and Life History 1996 and 1997 and IMBC unpublished data
Major Fishing Activity Areas	IMBC National Projects
Species 1996– 99 monthly catch	IMBC National Projects
Species 1984– 93 monthly landings	Greek National Statistical Service

SST, SSS, and Chl-a were produced from the time-series of these datasets. These grids were placed in a stack and unsupervised classification was performed. The classification revealed four distinct geographic areas with certain value ranges of SST, SSS, and Chl-a. A simple map-overlay of the classification grid and total cephalopod catch distribution showed the relation of species distribution with the above environmental parameters. Second, a monthly distribution of SST anomaly for 1997 was produced from the time-series of the monthly SST dataset. A simple map-overlay of the monthly SST anomalies and monthly total cephalopod catch distribution showed the relation of species distribution with the spatial range of SST anomalies that is a strong indication of seasonal front areas and possible upwelling regions.

An attempt to model *L. vulgaris* offshore-inshore migrations was performed in the southwest part of the study area. The migration model is based on SST and SSS integration with constraints from species life history data (species-preferred minimum and maximum SST and SSS values). The species-preferred ranges of SST and SSS were divided in three equally-spaced groups: 'Group 1' described SST and SSS ranges that were close to species-preferred minimum SST and SSS values, 'Group 2' described ranges close to average SST and SSS values, and 'Group 3' described

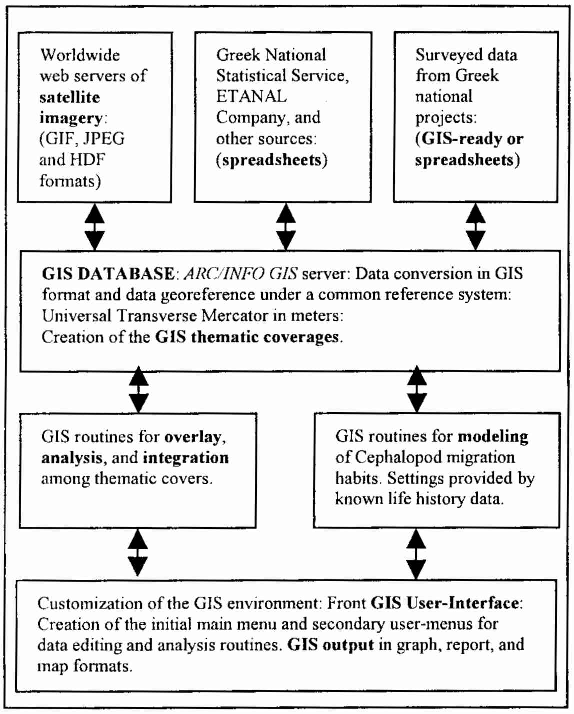

Figure 2. The architecture of the marine GIS development. Users have dynamic access to worldwide web servers as well as to the GIS database while they perform analytical tasks using only the associated fraction of the GIS database through user-interfaced routines.

ranges close to maximum SST and SSS values. These groups of SST and SSS values were placed in a grid with three 'cost-allocation' factors (1, 2, and 3), which revealed the 'difficulty' of a species to pass through a pixel based on species preferences in favorable environmental conditions (factor 2 being the most favorable). Finally, the model created a path among adjacent cells that contained the average 'cost-allocation' factor ('Group 2').

A series of GIS data selection and integration techniques is applied to the datasets for mapping seasonal suitable habitats of *I. coindetii*, a highly mobile cephalopod species. On a scale of 1:250,000, GIS integrations among datasets of different spatial resolutions are assumed acceptable. The first goal of these selections and integrations is to identify areas of potential species concentration and extract environmental conditions in these areas. Species concentration areas are considered as the common areas among species catch data, maximum occurrence depth, and major fishing activity. Based on the knowledge that *I. coindetii* is sensitive to temperature and salinity (Boletzky et al., 1973; Amaratunga, 1981; Hanlon and Messenger, 1996), the next goal is to use the values of the extracted environmental conditions on a monthly basis for identifying likely species-preferred areas for each environmental variable. The final GIS mapping of species seasonal suitable habitats is extracted by considering only these geographic areas where all species-preferred environmental variables are present. The list of these data selections and integrations is presented in Table 2.

Table 2. List of GIS integrations among vector, raster datasets and species life history data for the final mapping of Illex coindetii predicted suitable habitats.

Integration datasets	GIS Analysis Type	Result
General total catch cover (rectangle system)	Selection for species catch more than 0 Kg	Geo-distribution of species catch
a. Geo-distribution of species catch. b. Species maximum depth of occurrence (bathymetric dataset and species life history data)	Spatial integration between polygon coverages	Geo-distribution of species major occurrence areas
a. Geo-distribution of species major occurrence areas b. Fishing activity areas	Spatial integration between polygon coverages	Geo-distribution of species concentration areas
a. Geo-distribution of species concentration areas b1. SST, Chl-a, SSS Jan. image b12. SST, Chl-a, SSS Dec. image	Spatial selection between a polygon coverage (vector) and an image (raster)	Minimum and maximum values of species SST, Chl-a, and SSS preferences per month
a. Minimum and maximumvalues of species SST, Chl-a, and SSS preferences per month b. SST, Chl-a, SSS monthly grids	Spatial selection in a grid using certain min. and max. values and conversion in polygons	Areas of species preference based on SST, Chl-a, and SSS min. and max. values
Final Integration: Areas of species preference in: SST, Chl-a, and SSS.	Spatial integration among polygon coverages	Species predicted suitable habitats on a monthly basis

Results

GIS integration outputs for mapping species catch and landings geo-distributions, species occurrence and catch areas are presented in Figure 3A: A1-A4 *I. coindetii*, B1-B4 *L. vulgaris*, C1-C4 *Eledone* spp., D1-D4 *O. vulgaris*, and E1-E4 *S. officinalis*. It is noted that cephalopod total landings percentages (1984–93) are as followed: North Aegean Sea fish-markets: 64%, Central Aegean: 22%, and each of South Aegean and Ionian Seas fish-markets: 7%. Geo-distributions of species catch and landings are either dispersed in the whole study area (*L. vulgaris* and *S. officinalis*) or concentrated in the north part of the study area (*I. coindetii*, *Eledone* spp., and *O. vulgaris*). The surveyed total catch per species per month in the period 1996–99 is presented in Figure 3B.

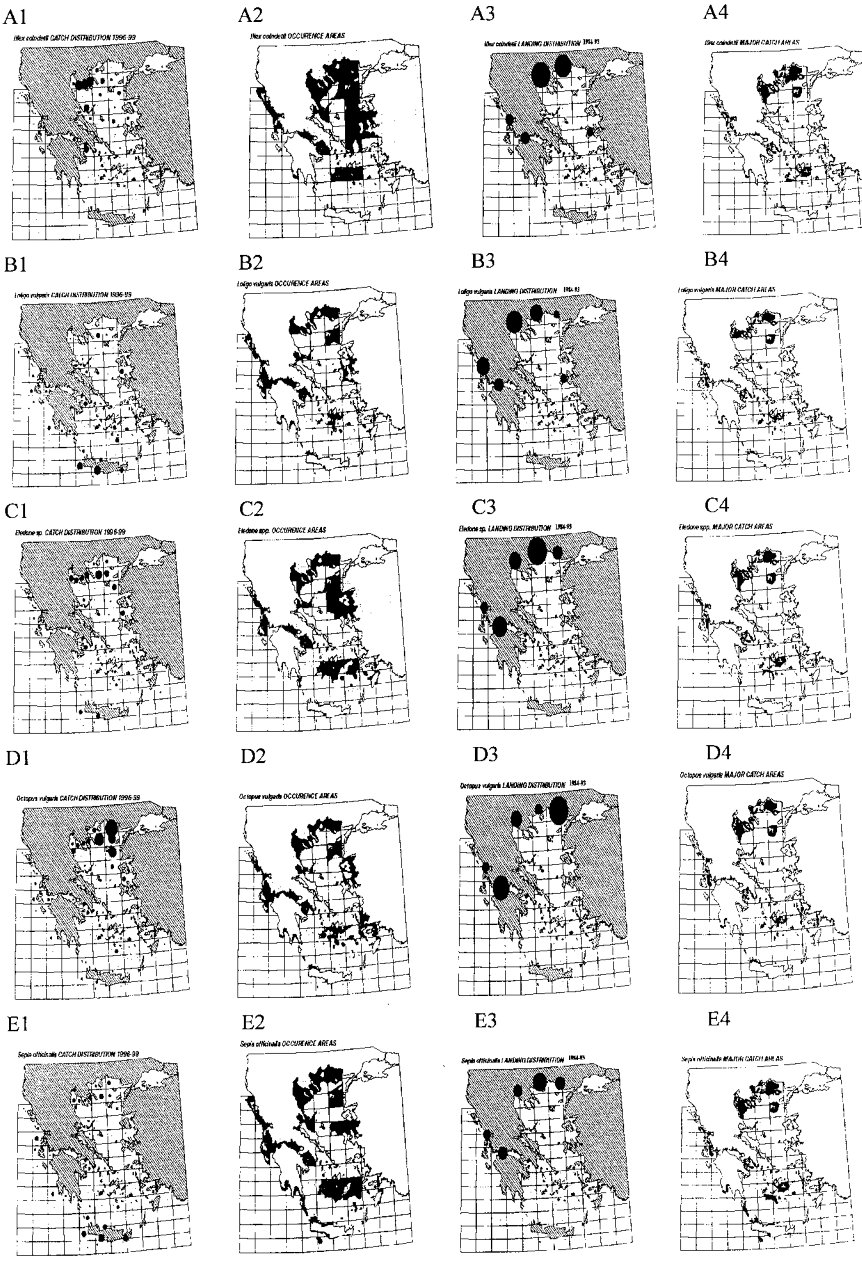

Figure 3A. Species geo-distributions in the Greek Seas (catch: 1996–99, landings: 1984–93). Geo-distributions of species catch and landings are either dispersed in the whole study area (*Loligo vulgaris* and *Sepia officinalis*) or concentrated in the north part of the study area (*Illex coindetii*, *Eledone* spp., and *Octopus vulgaris*).

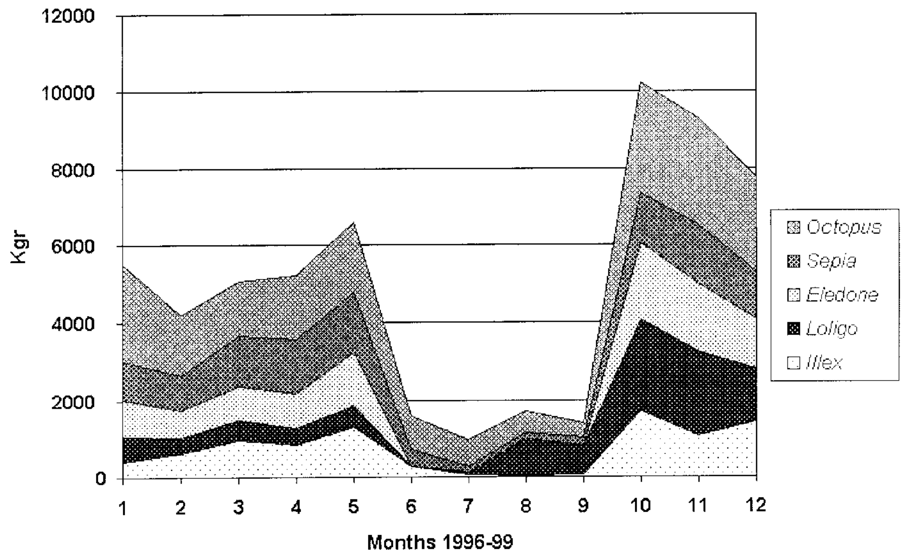

Figure 3B. Species monthly catch data for the period 1996–99 in Greek waters. The decrease in commercial catch rates during summer months is associated to the prohibition of trawling activity.

Mapping of likely species spawning locations in selected areas in North Aegean Sea and Crete Island are presented in Figure 4 (*L. vulgaris* and *S. officinalis*). It is suggested that these species prefer spawning areas that are located away form heavy anthropogenic pressure (see discussion).

The environmental variation of cephalopod catches is presented in Figure 5. The relation between total cephalopod catch and the classification of surface waters reveals that the majority of the catch is concentrated in areas with mean SST of 18.4°C, mean Chl-a of 0.18 mg m^{-3}, and mean SSS of 36.13‰. The relation between monthly total cephalopod catch and the anomalies of SST distribution in January 1997 shows that catch is associated with certain oceanographic phenomena (fronts and/or upwellings).

Modelled *L. vulgaris* migrations in the southern Greek Seas are presented in Figure 6 and compared with similar migrations of the species in the Gulfe de Lions (South France). Offshore-inshore species migration paths (during July) are compatible with an existing anticyclonic gyre (Pelops) during summer as well as with offshore catch data in the region.

The final integration maps of *I. coindetii* suitable habitats are shown in Figure 7. Results are based on species life history data on habitat, biology, and migration habits and show the decrease of *I. coindetii* populations during summer, their expansion during winter and their southern migration for spawning during spring.

Discussion

Geo-distributions of species catch and landings are either dispersed in the whole study area or concentrated in the north part of the study area. Satellite imagery shows a higher production in the north part of the study area (North Aegean Sea), an area that is more nutrient-rich as compared to the south part of the study area (South Aegean and Cretan

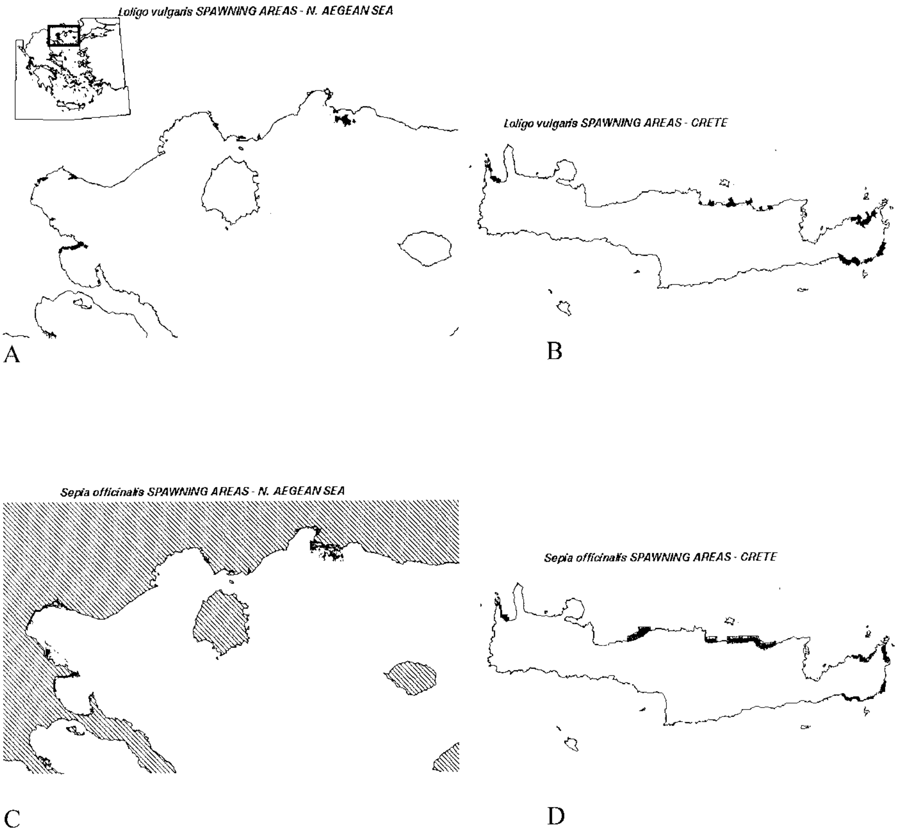

Figure 4. Predicted spawning areas. *Loligo vulgaris* (A and B) and *Sepia officinalis* (C and D). These areas are output of GIS integration among SST, substrate types, and bathymetry and include *Loligo vulgaris* spawning preferences in 10-25°C, on hard subsrtate of up to –100 m depth with spawning season during December–February and *Sepia officinalis* spawning preferences in 10–30°C, on muds and sands of up to –50 m depth with spawning season during March–July.

Seas). Sea surface chlorophyll-a concentration in North Aegean Sea is higher than that in South Aegean Sea by one order of magnitude (Poulos et al., 1997; Drakopoulos et al., 2000). Geo-distribution of species occurrence areas reveals the same patterns and provides a general picture of the geographic distribution of species populations. Geo-distribution of major catch areas shows that fishing activity is concentrated on the continental shelf and plateaux areas with a depth limit of approximately -500 m. Trawling is the major fishing gear for cephalopod fisheries in Greek waters.

Geo-distributions of potential spawning grounds (*L. vulgaris* and *S. officinalis*) in selected areas suggest that species prefer to spawn closer to the coast when a sharp-rocky coastline is present and away from the coast when a smooth-sandy beach is present. A verification test of GIS output for *L. vulgaris* spawning grounds was performed in Crete during February 1999. Members of the IMBC scientific diving team found *L. vulgaris* eggs attached on *Sargasso* spp. in a sandy bottom at –20 m in 18°C. It is ob-

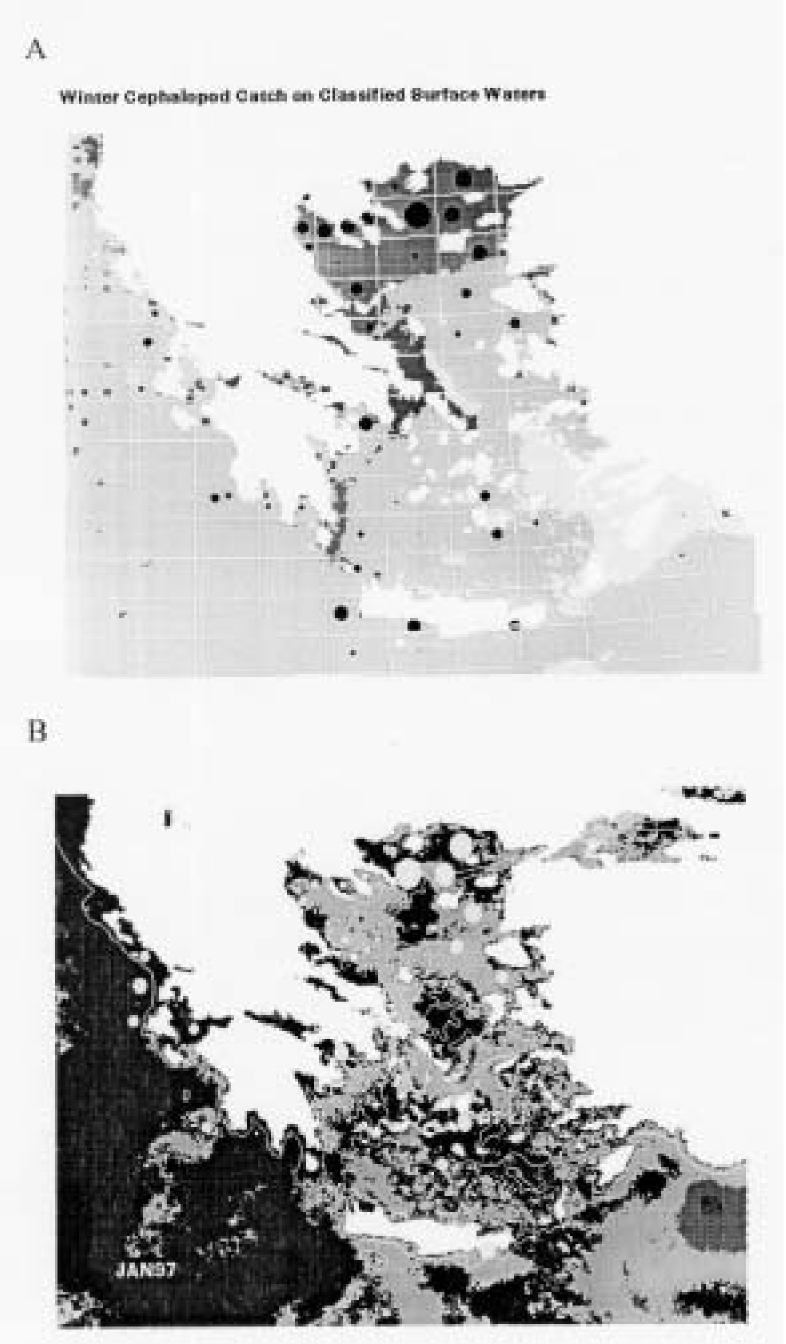

Figure 5. Environmental variation of cephalopod catches. (A) Total cephalopod catch (black spots) on SST/SSS/Chl-a classified surface waters during 1997. Unsupervised classification of surface waters was based on their sea surface temperature, salinity, and chlorophyll-a content (SST: 13.28–24.77°C, SSS: 34.21–38.27‰, and Chl-a: 0.05–0.21 mg m^{-3}). Darker areas show nutrient-rich, less saline, and colder surface waters. (B) Total cephalopod catch on SST anomaly in January 1997. The bathymetric contour of -600 m (boundary of continental shelf) is shown. The major part of the catch is associated with SST anomaly distribution and/or the boundaries of the continental shelf.

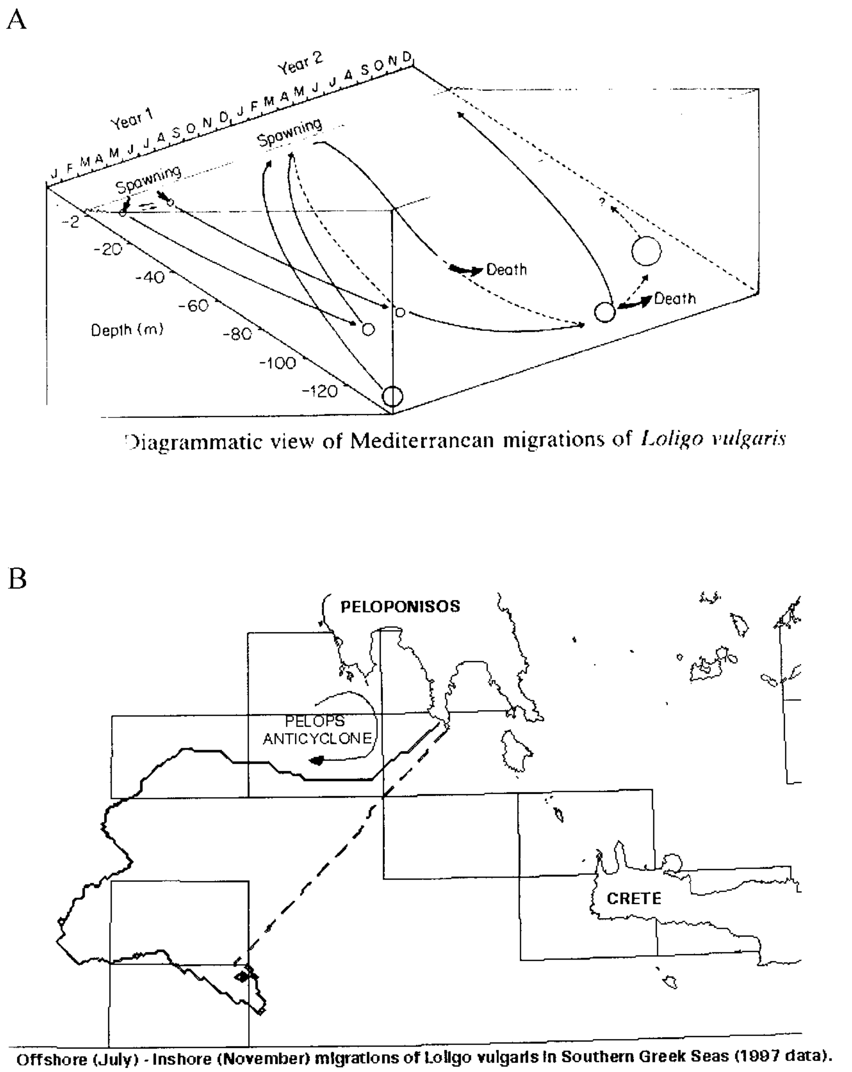

Figure 6. *Loligo vulgaris* offshore-inshore migrations. (A) A diagrammatic view of migrations in the Gulfe du Lion, located south of France, Mediterranean (Boyle, 1983). (B) Modelled migration paths of offshore (black line) and inshore (dashed line) migrations in the southern Greek Seas (Eastern Mediterranean). Rectangles show the presence of *Loligo vulgaris* catch data.

served that the location of spawning areas in North Aegean Sea falls inside areas of major fishing activity.

Classification of surface waters shows species preferences on ranges of temperature, salinity, and chlorophyll-a. The majority of the catch (North Aegean Sea) falls inside one of the classification clusters revealing species preferences in certain environmental conditions. Anomalies in sea surface temperature show that a major part of the catch is concentrated near the edges of the anomalies (strong indication of front and/or upwelling regions). Another part of the catch is concentrated near the edge of the continental shelf and plateaux. These patterns are also observed in SW Atlantic, where *I. argentinus* catch

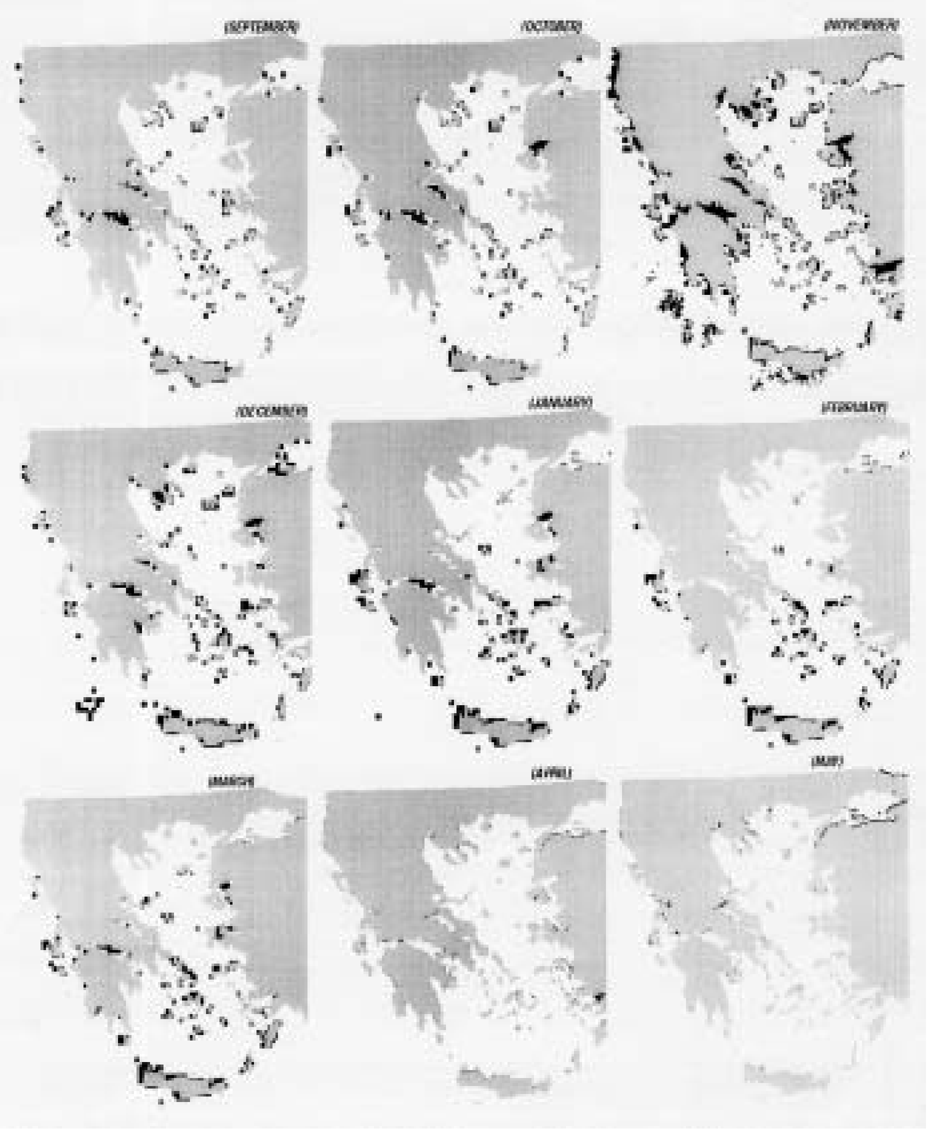

Figure 7. *Illex coindetii* predicted suitable habitat areas for the period 1996–99 on monthly basis. The derived environmental values that satisfy these areas are: MinSST: 3 C, MaxSST: 29 C, MinChl-a: 0.30 mg m^{-3}, MaxChl-a: 15.60 mg m^{-3}, MinSSS: 36.12‰, MaxSSS: 38.51‰.

areas were found to be associated with areas of thermal gradients at the interface of Falkland Current and Patagonian shelf waters (Waluda et al., in press).

Offshore migrations for *L. vulgaris* are related to sexual maturity and occur during early summer when matured individuals search for offshore feeding grounds (Boyle, 1983). After copulation and spawning (March–July), first the males and then the surviving females migrate offshore to deeper regions and as far as 200 km from the coast (Boyle, 1983). During wintertime (November–February), they migrate inshore and males arrive in coastal areas slightly before the females for spawning (Tinbergen and Verwey, 1945; Boyle, 1983). Modelled *L. vulgaris* migration paths agree with the presence of catch data in southern Greek Seas.

The GIS mapping of *I. coindetii* predicted suitable habitats for 1996–99 revealed the spatio-temporal distribution of known life history information on the species habitat, biology, and migration habits. During summer months (June-July-August), trawling activity is officially prohibited in the study area. The fact that no areas of suitable habitat are found during this period may be related to decreased summer productivity in the area (Drakopoulos et al., 2000), which results in species decreased growth rates from a limited food supply (Amaratunga et al., 1980) as well as species post-spawning high mortality (Roper, et al., 1984). It is suggested that *Illex* populations do not have any specific areas of aggregation during summer months. During fall and winter months, species growth rate increases and as a highly mobile and opportunistic species, they migrate offshore to take advantage of upwelling regions and associated plankton blooms (Boyle, 1983). Winter offshore upwelling events in the study area occur at locations around Antikithira Strait and southwest 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).

As mentioned above, *I. coindetii* predicted suitable habitats (Fig. 7) depict the geo-distribution of species-preferred living environmental conditions (life history data). Comparing these results with the geo-distribution of species monitored catch data (Fig. 3A,B) three trends are revealed: (a) most of coastal areas identified as predicted suitable habitats contain species in the monthly-monitored catch data (kg per month per statistical rectangle) (b) the increasing areas of predicted suitable habitats during November and December agree with the increase in commercial catch during this period, (c) offshore areas of predicted suitable habitats during November and December contain species monthly-monitored catch data.

Final Remarks and Conclusion

A variety of remotely sensed, surveyed, statistical, and cephalopod species life history data were analysed through a series of GIS integrations resulting in the seasonal mapping of species population dynamics. Marine GIS analysis routines are interfaced in one marine GIS tool. Through this tool, mapping of species catch and landings distribution, predicted occurrence areas, major catch locations, predicted spawning grounds, modelled migrations, predicted suitable habitats, and effects of several environmental parameters to population dynamics were discussed. An innovative approach of the marine GIS integration routines was the introduction of species life history data to GIS analysis. Some testing of predicted results was performed. Results on predicted spawning grounds for *L. vulgaris* in Crete were tested through on-site scientific dives while results on *I. coindetii* predicted suitable habitats in Greek Seas were tested through validation from species fishery and survey data.

The introduction of species life history data to GIS analysis is a new approach in the study of species population dynamics through information technology. This approach seems to be promising in the study of species that are sensitive in certain environmental conditions (temperature, salinity, etc.). We believe this approach will be applied to species other than cephalopods, as well.

Cephalopod fisheries in the Greek waters of SE Mediterranean are multi-gear with trawling being the major fishing tool, as it happens to many in-shore fisheries around the globe. Standardization of monitoring data about these fisheries will enhance the objectivity of management systems, which use information and satellite technology for the identification of several spatio-temporal patterns in the dynamics of species populations.

The expanding applications of GIS technology and use of Remote Sensing data in fisheries constitute a new field in marine fisheries GIS developments. Currently, as integrated fisheries monitoring with port sampling, landings recording as well as use of electronic log-books and on-board sea observers continually being developed and established, these GIS-based data analysis tools will be useful in information-based integrated management of commercial marine resources.

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