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Abstract

The study of small pelagic fish by hydroacoustic methods in the Mediterranean Sea began in the Adriatic in the 1950's. Since 2009, internationally coordinated, extensive, regular surveys have been conducted in the framework of the MEDIAS - *Mediterranean International Acoustic Surveys* – action, under the EU Data Collection Framework, to provide inputs for the management of small pelagics, particularly European anchovy (*Engraulis encrasicolus*) and European sardine (*Sardina pilchardus*). The surveys cover EU Mediterranean waters and monitor the distribution and abundance of small pelagic species using a common protocol. The hydroacoustic surveys, historically conducted by each EU State separately, have since been standardized and harmonized. We review their evolution from the beginning to the present and discuss their future prospects. We also report the historical time series of anchovy, sardine and other small pelagics in different areas and describe the spatial and temporal distribution of small pelagic species in decadal maps of the major areas of their distribution in the European Mediterranean Sea. Furthermore, we discuss the use of MEDIAS data for stock assessment purposes, the collection of auxiliary information for an Ecosystem Based Management (EBM) approach, the need for further standardization and future challenges.

Keywords: Acoustic survey; Mediterranean Sea; small pelagic; anchovy; sardine; MEDIAS.

Introduction

In the Mediterranean Sea, the study of small pelagic fish by hydroacoustic methods began in the 1950's. The early experiments, conducted in the Adriatic Sea in 1957 and 1963 (Kačić, 1972a; Vučetić & Kačić, 1973), were followed by pilot hydroacoustic surveys carried out in 1975 in the Adriatic Sea (Azzali & Levi, 1976; Kačić *et al.,* 1976; Azzali & Burczynski, 1977), south of Majorca (Oliver & Bravo de Laguna, 1976) and in the Gulf of Lions (Sacchi, 1975). Fisheries acoustics were soon recognized as a powerful tool to monitor the biomass and/or abundance of small pelagic species and became a common research method that was adopted by several countries (Machias *et al.,* 1997; Azzali *et al.,* 2002; Tičina *et al.,* 2006, Leonori *et al.,* 2012a). These early Mediterranean hydroacoustic surveys were based on protocols defined at the national level and applied hydroacoustic survey methodology (Simmonds & MacLennan, 2005; Jech & Michaels, 2006) widely used all over the world to study small pelagic fish. The typical operating frequency used to estimate the biomass of small pelagics was 38 kHz. The chief aim of hydroacoustic surveys was to directly evaluate population abundance, biomass and spatio-temporal species distribution. Fisheries acoustics – combined with direct observation (e.g., net sampling to identify target size and species composition) to ensure echo trace identification – allowed estimating the abundance and biomass of biological communities by species or species groups.

Since 2009, based on European Council Regulation EC 199/2008, extensive, regular, internationally coordinated hydroacoustic surveys have been conducted in the framework of the EU Fisheries Data Collection Regulation (DCR) to evaluate stock abundance and distribution, independently of the data provided by commercial fisheries and to support scientific advice regarding the Common Fisheries Policy (CFP) in the Mediterranean. The main objectives of these mandatory surveys, which were named MEDIAS (Mediterranean International Acoustic Survey), (http://www.medias-project.eu/medias/website/), are to assess the abundance and biomass of European anchovy (*Engraulis encrasicolus*, Linnaeus 1758) and European sardine (*Sardina pilchardus*, Walbaum 1792) and their spatial and temporal distribution in the Mediterranean based on the use of a common protocol (MEDIAS, 2019). Anchovy and sardine are the most abundant and commercially important small pelagic fish species in the Mediterranean (Lleonart & Maynou, 2003; FAO, 2016; Barange *et al.,* 2018). Their abundance indices obtained from hydroacoustic data are used as fishery-independent tuning indices in analytical stock assessment models based on fisheries catch (e.g., Aegean Sea: Antonakakis *et al.,* 2011; Giannoulaki *et al.,* 2014; Adriatic Sea: Carpi *et al.,* 2015; Spanish waters, Strait of Sicily, Adriatic Sea, Aegean Sea: GFCM WGSASP, 2019, 2020), surplus production models (e.g., Ligurian and Tyrrhenian Sea: GFCM WGSASP, 2019) or assessment methods relying solely on information obtained from scientific surveys at sea (e.g., Gulf of Lions: GFCM WGSASP, 2019).

This review describes the beginnings, the present and the future prospects of the MEDIAS action, its coverage and resolution in EU Mediterranean waters, its main methods and outputs, the contribution of hydroacoustics to ecosystem knowledge and the indicators that are derived from hydroacoustic survey data. In particular, it reports the historical time series of anchovy and sardine biomass assessed by hydroacoustic methods in different areas of the Mediterranean, the spatial and temporal distribution of small pelagic species as decadal maps, the use of MEDIAS data for stock assessment purposes and the collection of auxiliary information for an Ecosystem Based Management (EBM) approach. The ecosystem indicators that can directly be obtained from the hydroacoustic data, the information that could also be gathered and the movement towards survey standardization are also described. Finally, the need for further survey standardization and future challenges are discussed.

Coverage

In the past ten years, the coverage of the hydroacoustic surveys in the European Mediterranean Sea has been expanded to encompass the main European Mediterranean waters inhabited by small pelagic fish (Fig. 1, Table S1), although some areas remain to be covered. Figure 1 shows the General Fisheries Commission for the Mediterranean (GFCM) Geographical Sub-Areas (GSAs), established in the resolution GFCM/33/2009/2 (GFCM,

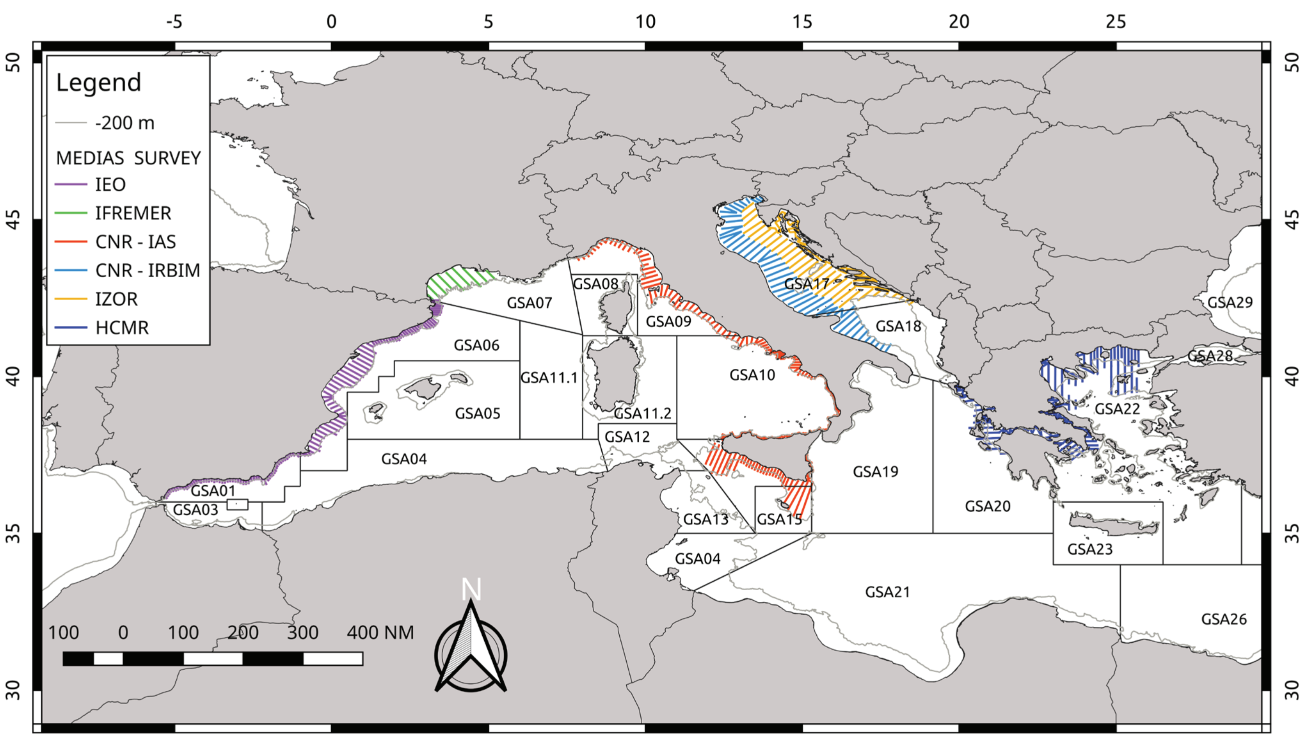

Fig. 1: MEDIAS survey design. Map of transects covered by the MEDIAS surveys and GFCM Geographical Sub-Areas (GSAs) in the European Mediterranean Sea.

2009), for stock assessments in the Mediterranean and Black Seas http://www.fao.org/gfcm/data/maps/gsas). As the Mediterranean Sea is considered oligotrophic and is highly heterogeneous in terms of hydrography, bathymetry and productivity (Bethoux *et al.,* 1999; Colella *et al.,* 2016), the surveys are conducted on the continental shelf from a depth of 15-30 m to ~ 200 m, where small pelagic fish are mainly distributed.

Acoustic Data Collection

Beginning and evolution of the hydroacoustic survey activities in each MEDIAS area

Adriatic Sea

The first trials using scientific echo sounders in the Mediterranean were conducted in 1957 and 1963 (Kačić, 1972a) by scientists of the Institute of Oceanography and Fisheries (IOF) of Split (then Yugoslavia), to discover new sardine fishing grounds in the eastern Adriatic Sea. In 1968-74, further experiments (Fig. S1) were undertaken to collect information about the relative abundance and distribution of small pelagics for the commercial fishing fleet (Kačić, 1972b, 1972c, 1974; Grubišić *et al.,* 1974). In July 1975, the evolution of fisheries acoustics allowed a pilot hydroacoustic survey for assessment purposes to be conducted in the Northern Adriatic (GSA 17) by Italian, Yugoslav and French scientists on board the R/V *Salvatore Lo Bianco* (Azzali & Levi, 1976; Kačić *et al.,* 1976; Azzali & Burczynski, 1977) (Fig. S2, Table S1). *Ex situ* fish cage trials for target strength (TS) measurements were carried out in Sistiana Bay (Gulf of Trieste; Azzali, 1977, 1983) using the Simrad EK38S echo sounder (Fig. S3) and a Simrad QM-MK II echo integrator (Azzali, 1979, 1980). After the Treaty of Osimo (10 November 1975), the hydroacoustic surveys were carried out on the two sides of the midline agreed on by the Italian and Yugoslav governments: the CNR scientists from Ancona (Italy) performed hydroacoustic surveys on the western side of GSAs 17 and 18, whereas the IOF scientists from Split conducted them on the eastern side of GSA 17.

In Italy, an annual hydroacoustic survey (ECHOADRI) was conducted in western GSA 17 in summer-early autumn since June 1976 (Azzali *et al.,* 1980, 1983, 2002; Azzali, 1981a, 1981b, 1981c; Leonori *et al.,* 2012a), providing the first hydroacoustic estimates of the biomass of small pelagic populations in the Northern Adriatic. In 1987, the survey was extended to the south-western Adriatic Sea (GSA 18) to cover a total area of ~ 13,400 nm^2 (Fig. 1) (Azzali *et al.,* 1997, 2002; Leonori *et al.,* 2007, 2011a). Its chief aim was to assess the biomass and spatial distribution of anchovy, sardine and sprat (*Sprattus sprattus*, Linnaeus 1758) on the Italian side of the Adriatic. It was conducted aboard the R/V *Salvatore Lo Bianco* until 1998 (Table S1), aboard the R/V *Thetis* in 1999-2000 and aboard the R/V *Dallaporta* since 2001. The Simrad EK400, used since 1993, was replaced by the EK500 and in 2008 by the EK60 (Table S1). The EK80 at 70 kHz was added in 2015; the vessel is currently equipped with the Simrad EK60-80 (38, 70, 120, 200 kHz) echo sounder (Table S1). Scientists from various non-EU Countries have participated in the framework of several international collaborations (Leonori *et al.,* 2011b, 2012b). Since 2010, plankton sampling focusing on anchovy eggs and larvae has also been carried out (Malavolti *et al.,* 2018).

On the eastern side of the Adriatic, occasional small-scale surveys, aimed at collecting information on small pelagic fish for commercial fisheries, were undertaken in 1977, 1982 and 1986 in the same fishing areas (Fig. S1) on a monthly or seasonal basis (Kačić, 1980, 1988). They were conducted aboard the R/V *BIOS* (wooden hull, 27 m, 300 HP) – which was equipped with the Simrad 540-4 (30 kHz) echo sounder, the EH and EK38A (38 kHz) sounders and a QM MARK II echo integrator (Fig. S4) – to study the behaviour of small pelagic fish and estimate their relative abundance. In 2001, IOF and CNR scientist conducted a joint pilot survey in the eastern Adriatic that also included a training course on acoustic survey procedures. From 2003 to 2010, the Croatian Ministry of Agriculture and the IOF conducted a national annual acoustic survey (PELMON) throughout the Croatian territorial waters and within the Ecological and Fishery Protection Zone (ZERP) that borders the midline, surveying a total area of ~ 13,500 nm^2 (Tičina *et al.,* 2006). The PELMON multidisciplinary surveys of the pelagic ecosystem were carried out in September on board the R/V *BIOS*, which was equipped with the Simrad EK60 echo sounder (38 kHz). They targeted the same species as the surveys on the Italian side (i.e., anchovy, sardine and sprat) and used the same TS equations for hydroacoustic data conversion (Leonori *et al.,* 2017), to obtain direct estimates of fish biomass in the study area (Tičina *et al.,* 2006). An intercalibration exercise between the R/V *BIOS* and the R/V *Dallaporta* was performed in 2005 in the Neretva Channel, on the southern Croatian coast (Leonori *et al.,* 2012a), to compare their hydroacoustic and biological sampling properties. A new ship, the R/V *BIOS DVA* (steel hull, 36 m, 1200 HP), in use since 2009, was equipped with the same fish sampling equipment as the R/V *Dallaporta.* The surveys conducted in 2011-12, before the accession of Croatia to the EU in 2013, covered only half the current area and aimed primarily at achieving harmonization with the EU MEDIAS standards and protocol (Fig. 1). The current echo sounder, the Simrad EK80 (38 and 120 kHz), replaced the Simrad EK60 apparatus in 2018 (Table S1).

Mediterranean Spain

In Spain, the acoustic surveys were started by a team of scientists from the Balearic Oceanographic Centre of the Spanish Institute of Oceanography (IEO). The first training surveys were carried out in 1975, 1976 and 1977 aboard the R/V *El Pescador* using the Simrad EK38S echo sounder. In August 1975, the first small-scale pilot survey (Oliver & Bravo de Laguna, 1976) was conducted on the southern side of Majorca (GSA 05); Italian and

Norwegian researchers were also aboard (Table S1). After mastering the data acquisition and processing methodology, technological evolution entailed the acquisition of a succession of Simrad scientific echo sounders, from the EK400, the EK500, and the EK60 to the current EK80 apparatus, which is used to collect data on pelagic fish resources both in the Mediterranean and the Atlantic Spanish waters (Cantabrian Sea and Gulf of Cadiz). Notably, several international collaborations, mostly in the 1990s, involved training of scientists working in non-EU Countries and conducting fisheries assessments in international waters. In 1982, the Alsarev-82 survey was carried out with the Simrad EK400 echo sounder aboard the R/V *Cornide de Saavedra*; during this survey an intercalibration exercise was performed with the Norwegian *R/V Dr Fridtjof Nansen*. In 1983-1987, a series of hydroacoustic surveys (*Mediterráneo*) covering the Spanish continental shelf were carried out in October-November, except in 1987, when the vessel was available only in July. In 1988, the name of the project changed to ECOMED and the surveys were performed in May-June. In 1990-1996 a series of surveys were conducted in October-November and, from 1997 to 2009, in November-December. The aim of all these hydroacoustic surveys was to estimate the recruitment of European anchovy and the spawning stock biomass of European sardine (Table S1). In 2009, the Spanish surveys became part of the MEDIAS action, which includes all EU Mediterranean Countries. These surveys are performed in June-July to assess the spawning stock biomass and recruitment of anchovy and sardine using shared standards and protocols. Data are systematically collected along 111 parallel transects perpendicular to the coastline, covering GSA 01 (Northern Alboran Sea) and GSA 06 (Northern Spain). The surveyed area measures ~ 8,800 nm^2 (Fig. 1). Since 2013, the surveys have been carried out aboard the R/V *Miguel Oliver* using the Simrad EK60 echo sounder (Table S1).

Gulf of Lions

In the Gulf of Lions, fisheries acoustic research started with three pilot surveys carried out on board the *R/V Ichthys* in 1975, 1977 and 1978 (Sacchi, 1975; Farrugio, 1977, 1978) and involved practical and theoretical investigations using the Simrad EQ echo sounder (Table S1). Next, two surveys conducted on board the *R/V Thalassa* in 1984 and 1985 involved the collection of hydroacoustic data using the Simrad EK400 echo sounder. Standardized hydroacoustic surveys of small pelagic fish experienced a slow start and began to be performed at annual intervals only in 1992, with the PELMED (*PELagiques MEDiterranée*) survey (Bourdeix & Hattab, 1985). In 1992, the survey was conducted on board the *R/V Roselys II* and in 1993 on board the R/V *Thalassa;* then, from 1994 onward the survey was carried out exclusively on board the R/V *L'Europe*, which was equipped with a MICREL Ossian 1500 echo sounder that was replaced by the Simrad EK500 apparatus in 2000 and by the Simrad EK60 echo sounder in 2012 (18, 38, 70, 120, 200 and 333 kHz) (Table S1). More recently, Ifremer and Simrad have developed a fully calibrated fisheries research multibeam echo sounder, the ME70, that was installed on the R/V *L'Europe* in 2014 (Trenkel *et al.,* 2008). The PELMED survey is commonly conducted in June-July (in August in 1995). Since 1993, data are systematically collected along 9 parallel transects perpendicular to the coastline (total length, 355 nm or 22 km) set 12 nm apart (Fig. 1). The surveyed area measures ~ 3,300 nm^2.

Ligurian Sea, Tyrrhenian Sea and Strait of Sicily

Pilot hydroacoustic surveys were conducted in the Tyrrhenian Sea in 1986 (August-September) and in the Strait of Sicily in 1987 (June) on board the R/V *Salvatore Lo Bianco* (Azzali *et al.,* 1988) (Table S1). The acoustic surveys in the Ligurian Sea (GSA 09) and the Tyrrhenian Sea (GSA 10) began in summer 2009. They were conducted in the framework of various Italian research projects on board the R/V *Dallaporta* and employed the MEDIAS protocol (Table S1, Fig. 1). The surveyed area measured ~ 6,300 nm^2. In 2010 and 2012, no project envisaged surveying the Ligurian and the Tyrrhenian Seas. Since 2017, the surveys in these GSAs are conducted as part of the EU DCF (Bonanno *et al.,* 2016). In the Strait of Sicily (GSA 16), the annual survey began in summer 1998 (Table S1) in the framework of national and international research projects. It was conducted aboard the R/V *Salvatore Lo Bianco* in 1998 and aboard the R/V *Thetis* in 1999-2000; since 2001 it is performed aboard the R/V *Dallaporta* (except in 2010, when it was carried out aboard of R/V *Maria Grazia*). The surveyed area measures ~ 3,500 nm^2 (Fig. 1). Since 2009, this hydroacoustic survey is part of the EU DCF (Basilone *et al.,* 2013; Barra *et al.,* 2015). The vessel has been equipped with the Simrad EK60 apparatus (38, 120, 200 kHz) since 2005 (Table S1).

Eastern Ionian Sea and North Aegean Sea

The history of the hydroacoustic surveys in Greek waters dates back to 1987 and the NATO Science for Stability (SFS) program. The early period of the program coincided with the construction of the Marine Research Centre on Crete, which, together with several other large projects, was undertaken to stimulate the growth of a high-tech industry on the island through the creation of specialized institutes. The SFS program also funded the construction of the R/V *Philia* – which was equipped with the Simrad EK400 echo sounder (38 and 120 kHz) – and marked the beginning of fisheries acoustics in Greek waters (Table S1). The first hydroacoustic surveys, conducted in the North Aegean Sea (GSA 22) in 1987-1988, in the Central Aegean Sea in 1989-90 and in the South Aegean Sea in 1991, investigated the echo distribution of small pelagic fish assemblages (Tsimenides, 1989; Tsimenides *et al.,* 1992, 1995). Simultaneous hydroacoustic and egg surveys were carried out in the framework of various European and national projects in 1995-2001 to obtain direct estimates of anchovy and sardine biomass using a Biosonics Dual Beam echo sounder at 38 kHz (Tsimenides *et al.,* 1998; Machias *et al.,* 2001a, 2001b). A single-beam Furuno echo sounder (38 and 15 kHz) was also used in addition to these scientific echo sounders and was later replaced with a Scanmar RX apparatus. These surveys investigated the vertical and horizontal distribution of anchovy and sardine in the northern Aegean Sea and the coastal areas of the central Aegean and Ionian Seas (*e.g.* Machias *et al.,* 1996, 1997, 2001a, b; Giannoulaki *et al.,* 1999, 2003; Somarakis *et al.,* 2001). The experimental sampling and survey work was discontinuous both in time and space, since it was largely related to the existence and duration of the various research projects; as a result, a long regular time series of anchovy biomass and biological parameters throughout the Greek waters are not available. The R/V *Philia* – equipped with a Biosonics Split Beam DTX echo sounder – was employed to produce regular estimates of anchovy and sardine stocks in the Aegean Sea in June-July, in the framework of the Greek National Program for Fisheries Data Collection: data are available for 2002-2008 whereas there are gaps in 2009-2012 (Fig. 1). In the North Aegean Sea survey, anchovy stocks have traditionally been assessed simultaneously by the Daily Egg Production Method (DEPM) and acoustically along 70 transects set 10 nm apart and perpendicular to the coastline, covering an area of ~ 9,000 nm^2. Since 2013, the Eastern Ionian Sea (GSA 20) is also regularly surveyed in early autumn, covering an area of ~ 2,800 nm^2 with 40 transects perpendicular to the coastline (Fig. 1). In 2015, the R/V *Philia* was upgraded with a Simrad EK80 at 38, 120, 200 and 333 kHz.

The internationally coordinated Mediterranean Acoustic Survey (MEDIAS)

The MEDIAS Steering Committee was set up in 2007, on the occasion of the Regional Coordination Meeting (RCM) for the Mediterranean. It met for the first time during the first MEDIAS preparatory workshop (MEDIAS, 2008). Its agenda envisaged the formulation and adoption of a common protocol for the MEDIAS activities in the framework of the EU Data Collection Regulation (DCR), according to RCM recommendations and the decisions of the Liaison Meeting. International coordination meetings to promote and ensure survey standardization and harmonization are held annually. The MEDIAS action – involving surveys performed by research institutions from Spain, France, Italy and Greece within in the DCR (EC 665/2008) – officially began in 2009 (Giannoulaki *et al.,* 2011, 2013). Croatia joined in 2013, as a new EU member state. The surveys cover the continental shelf of the northern part of the Mediterranean Sea using a shared protocol (MEDIAS, 2019), in collaboration with Slovenian and Maltese scientists (Fig. 1). Since its adoption, the MEDIAS protocol - which is also shared with Romanian and Bulgarian researchers who conduct surveys targeting small pelagics in the Black Sea – has regularly been evaluated, improved, standardized and harmonized.

General principles

MEDIAS activities are conducted annually and are based on fisheries acoustics and pelagic trawl sampling. The information thus collected is used to assess internationally managed stocks and support management decisions. The surveys provide abundance and biomass estimates for anchovy and sardine, the MEDIAS target species. Although in theory they could also supply abundance indices for the major pelagic species in each area, the different technical resources available to member States hamper the provision of standardized biomass estimates for non-target species based on acoustics.

The hydroacoustic records are collected on board each research vessel using a scientific echo sounder with split-beam transducers (see Simmonds & MacLennan, 2005 for acoustics terminology and instruments). The principal assessment frequency is 38 kHz, while 18, 70, 120, 200 and 333 kHz are used as complementary frequencies depending on vessel instrumentation (Table S1). Based on the latest agreed protocol (MEDIAS, 2019), the hydroacoustic surveys are performed exclusively in daytime and are interrupted when the schools disperse. Pulse duration is 1 ms; the assessment threshold ranges from -70 to -60 dB, depending on the survey and the ecosystem of the area. To optimize echo discrimination, the ping rate is as fast as possible in relation to depth. The transducers are calibrated according to standard procedures (Foote *et al.,* 1987; Demer *et al.,* 2015).

The survey design consists of systematic line transects perpendicular to the coastline/bathymetry, or adapted to the geomorphology of the survey area. Geostatistical analysis has been applied to historical hydroacoustic data in the framework of the AcousMed project (Anonymous, 2012), to evaluate different survey designs and suggest how they could be optimized in relation to the spatial characteristics of small pelagic fish aggregations. Identification of the optimum inter-transect distance for each GSA was followed by its adoption (Fig. 1). The inter-transect distance was adjusted to minimize the coefficient of variation of the acoustic estimates for the target species in each area taking into account survey duration (≤ 12 nm). According to the MEDIAS common protocol, a vessel speed of 8-10 knots is considered appropriate for a split-beam echo sounder operating at 38 kHz, as higher speeds may pose problems with engine or hull noise or propeller cavitation. Given the coastal distribution of sardine, proper coverage of their spatial distribution would best be achieved by transects extending as close to the coast as feasible; therefore acoustic sampling should begin at least at a bottom depth of 20 m or less if possible. The minimum echo sounding depth clearly depends on vessel draught; the maximum has been set at 200 m, *i.e.* about the depth of the edge of the continental shelf, where the abundance of most small pelagic fish plummets.

As regards the hydroacoustic methodology, the Elementary Distance Sampling Unit (EDSU) for echo integration is 1 nm. Echo partitioning into species is based on visual scrutinization of echograms by direct allocation (*i.e.* identification of individual schools) and/or by allocation based on representative fishing stations. Hydroacoustic data analysis to assess the abundance of target species is performed with Echoview software (Echoview Software, Tasmania, Australia, http://www.echoview.com) or Movies 3D software. Fish density is estimated by the echo integration method (Simmonds & MacLennan, 2005; Chu, 2011). The MEDIAS protocol (MEDIAS, 2019) also includes a common workflow for hydroacoustic data processing. The procedure describes the steps to be followed during all process phases, including hydroacoustic data acquisition by the echo sounder, visual exploration of hydroacoustic data (echograms and maps), inclusion of calibration results in raw hydroacoustic data processing, removal of background noise prior to hydroacoustic data analysis and filtering of hydroacoustic data to remove backscatter signal due to reverberation (*i.e.* non-target echo traces). This last phase involves the use of grids, lines, regions and mathematical operators to exclude any backscattering signal not linked to the presence of fish and/or plankton from the collected hydroacoustic data. Specific aspects are background and intermittent noise removal and surface and seafloor exclusions. An estimation procedure has also been adopted to separate fish from planktonic organisms. Parameter values for the school detection method have also been agreed and added to the MEDIAS protocol.

It has been agreed that annual hydroacoustic surveys are to be conducted from June to September. Summer coincides with the peak reproductive period of anchovy and the peak recruitment period of sardine (e.g., Palomera *et al.,* 2007; Morello & Arneri, 2009). Pelagic trawl sampling is critical to collect representative samples of the fish population, to enable species identification by their echo traces and to determine objectively the size distribution of the population. Haul sampling intensity cannot be determined in advance. Vessel speed during pelagic trawl sampling should be 3.5–4.5 knots. The sampling strategy in terms of inter-transect distance must be adaptable to the main characteristics of the fish aggregations found in each area. Biological samples collected in the daytime and at night can be pooled for length frequency estimations (Machias *et al.,* 2013). The otolith reading criteria adopted for anchovy and sardine are in line with the ICES WKARA2 report (2017) and their reproductive phase is identified according to the ICES WKSPMAT report scale (2008).

Since the environmental parameters are critical for small pelagic fish, a grid of CTD stations is also sampled during the hydroacoustic surveys, to record the main oceanographic features of the area. The fields and algorithms required for a shared database have been investigated in the framework of the AcousMed project (Anonymous, 2012) and further improved in the MEDIAS coordination meetings, to facilitate the storage of all the acoustic and biological information collected during the hydroacoustic surveys. However, the database is still to be developed.

Characteristics of the European Mediterranean GSAs - Population dynamics - Spatial distribution of small pelagics

Since the 1970's, when the hydroacoustic surveys began in the Mediterranean Sea, the number of GSAs subjected to hydroacoustic monitoring has increased from one decade to the next (see section 3.1 and Table S1). The latest GSAs to be included in the annual MEDIAS surveys are the eastern Ionian Sea (GSA 20) and the north-eastern Adriatic Sea (eastern GSA 17), in 2013, and the Tyrrhenian and Ligurian Seas (GSAs 09 and 10), in 2017.

The small pelagic fish biomass estimates based on hydroacoustic data collected in EU Mediterranean waters are presented in Figures 2, 3 and 4. Some of these historical time series also cover periods prior to the MEDIAS action, in the countries where surveys were already conducted; here, the harmonization of the national protocols (MEDIAS, 2008) has not introduced major differences compared to the past. In the case of Spain, the standardization process involved a change in the period in which the survey was carried out, from November-December to June-July. Thus, a new separate time series is considered since 2009 (MEDIAS, 2008). In the other cases, the first MEDIAS meeting (MEDIAS, 2008) decided to keep the existing historical series, re-analysing past estimates where necessary. The time series are very important, because the temporal trend of the biomass estimates is useful for stock assessment and for the determination of the biomass reference points. The effect of changes of instrumentation on long series, due to the development of new technology, has also been taken into consideration. However, the manufacturers of the hydroacoustic instruments employed by the MEDIAS groups have consistently maintained high-level standards and have ensured that the new equipment provides comparable estimates.

The estimates highlight that although the Mediterranean Sea is considered an oligotrophic environment, the biomass values of small pelagic fish show broad temporal fluctuations, like small pelagics all over the world (Brander, 2007; Gushing & Dickson, 1977). The average abundance of small pelagic fish based on the MEDIAS surveys in the 2010's (2010 to 2018) is reported in Fig. 5 as Total Fish Nautical Area Scattering Coefficient *per* EDSU. The spatial distribution depicted in Fig. 5 shows that biomass levels are higher on the large continental shelf areas like the Adriatic and the Gulf of Lions, which are characterized by shallow bottoms and significant freshwater inputs. The 2019 biomass estimates are provided for *E. encrasicolus and S. pilchardus,* the main small pelagic species in Mediterranean, together with the geostatistical coefficient of variation (CV; Walline *et al.,* 2007) in Table 1. Other common pelagic species found in the GSAs covered by the MEDIAS include *S. sprattus, Sardinella aurita, Boops boops, Trachurus trachurus, Trachurus mediterraneus* and *Scomber colias*.

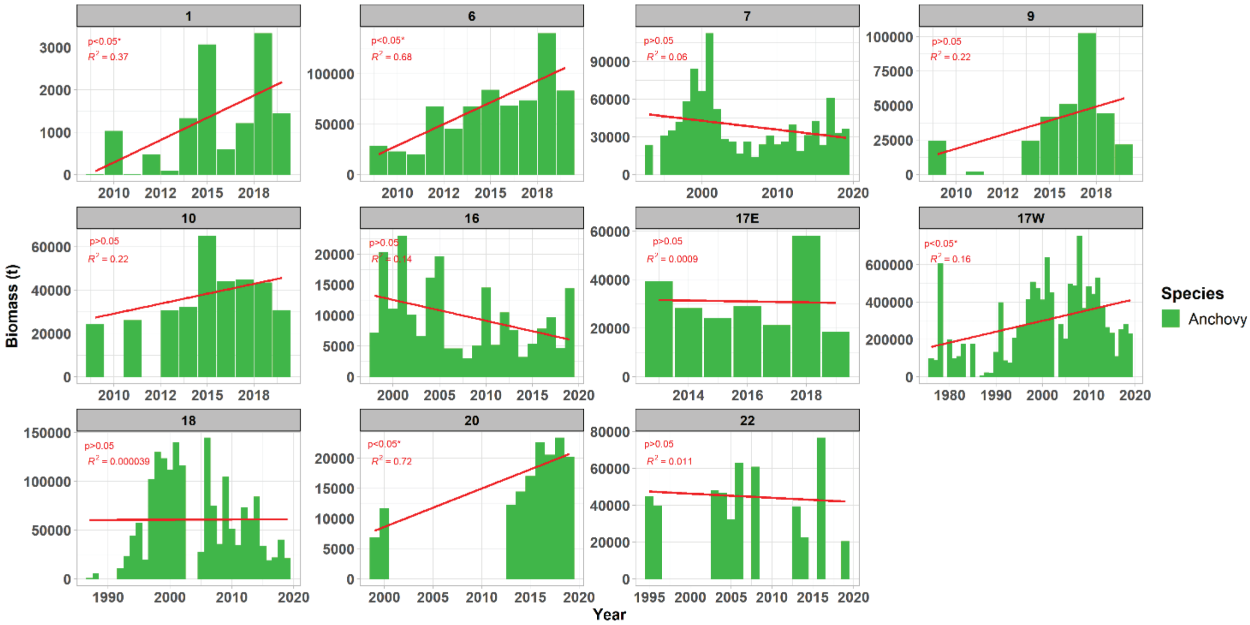

Fig. 2: Time series of the acoustic biomass estimates (tons) of anchovy in the European Mediterranean: (1) Northern Alboran Sea - GSA 01, (6) Northern Spain - GSA 06, (7) Gulf of Lions - GSA 07, (9) Ligurian Sea - GSA 09, (10) Tyrrhenian Sea - GSA 10, (16) Strait of Sicily - GSA 16, (17W) North-western Adriatic Sea - GSA 17 W, (17E) North-eastern Adriatic Sea - GSA 17 E with (18) South-western Adriatic Sea - GSA 18, (20) Eastern Ionian Sea - GSA 20 and (22) North Aegean Sea - GSA 22.

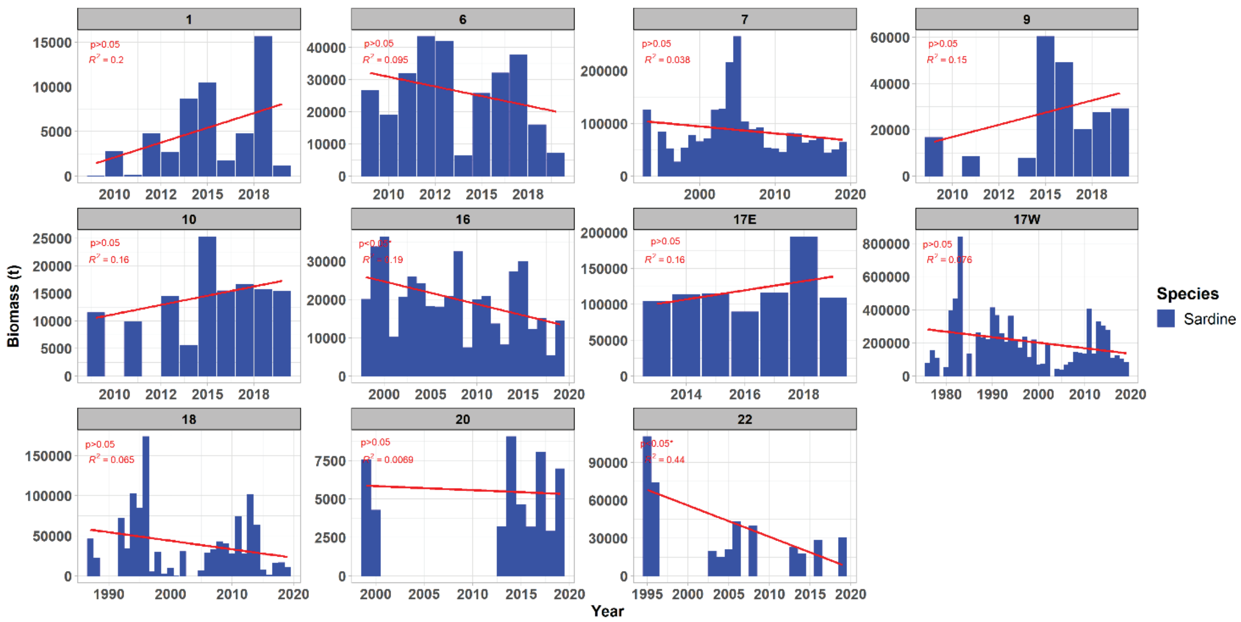

Fig. 3: Time series of the acoustic biomass estimates (tons) of sardine in the European Mediterranean Sea: (1) Northern Alboran Sea - GSA 01, (6) Northern Spain - GSA 06, (7) Gulf of Lions - GSA 07, (9) Ligurian Sea - GSA 09, (10) Tyrrhenian Sea - GSA 10, (16) Strait of Sicily - GSA 16, (17W) North-western Adriatic Sea - GSA 17 W, (17E) North-eastern Adriatic Sea - GSA 17 E with (18) South-western Adriatic Sea - GSA 18, (20) Eastern Ionian Sea - GSA 20 and (22) North Aegean Sea - GSA 22.

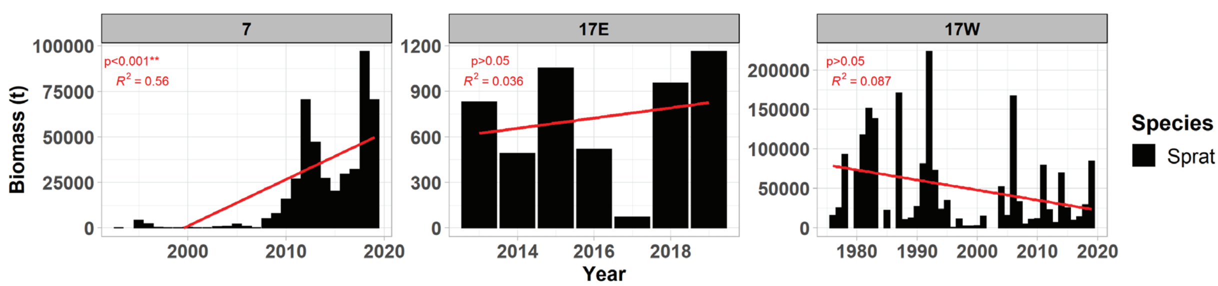

Fig. 4: Time series of the acoustic biomass estimates (tons) of sprat in the European Mediterranean Sea: (7) Gulf of Lions - GSA 07, (17W) North-western Adriatic Sea - GSA 17 W and (17E) North-eastern Adriatic Sea - GSA 17 E.

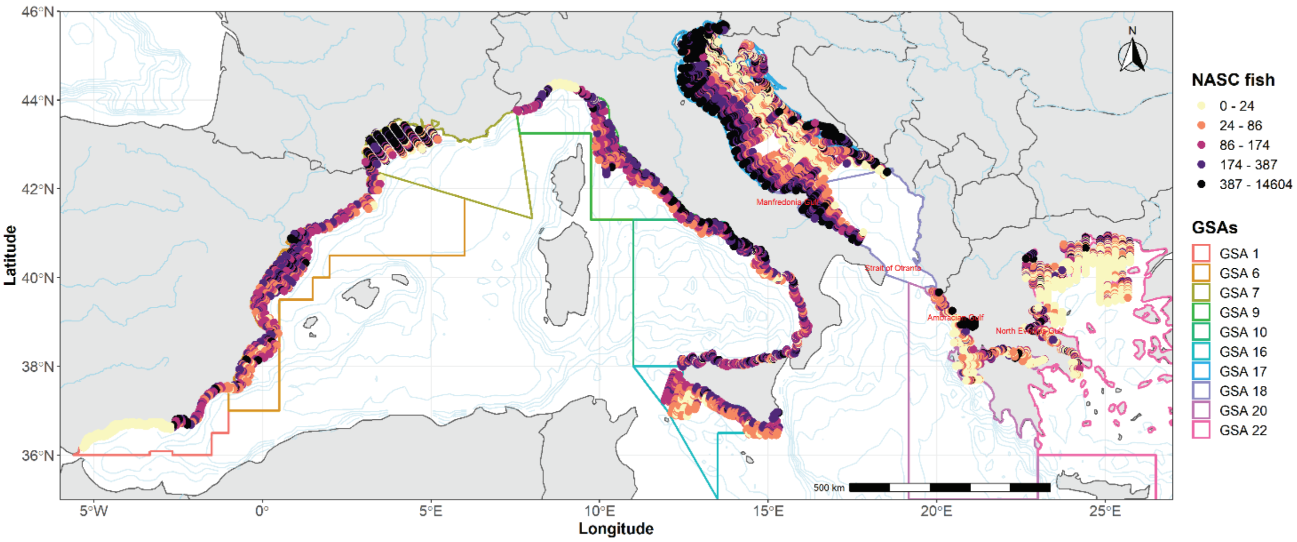

Fig. 5: Abundance of small pelagics expressed as Total Fish Nautical Area Scattering Coefficient (NASC, m^2 nm^{-2}) *per* EDSU (Elementary Distance Sampling Unit) calculated as decade average (2010-2018 period) in the European Mediterranean Sea.

Table 1. Biomass (tons) and associated geostatistical coefficient of variation (CV) of the anchovy and sardine estimates in the MEDIAS surveys *per* GSA in 2019.

GSA	Area	Anchovy		Sardine	
	nm^2	Biomass	CV (%)	Biomass	CV (%)
1	2,800	1,424	14	1,107	13
6	6,000	82,951	7	7,036	9
7	3,300	36,168	12	63,311	18
9	3,600	21,394	17	28,970	13
10	2,600	30,483	15	15,360	14
16	3,400	14,301	12	14,410	20
17 E	13,500	18,232	10	109,064	11
17 W	10,800	229,856	9	82,666	11
18	2,600	20,495	15	10,503	17
20	3,000	20,066	8	6,938	19
22	9,000	20,150	9	30,235	16

Western Mediterranean Sea

In GSA 01 - *Northern Alboran Sea*, nutrients are mainly supplied by coastal upwelling processes that drive the abundance of small pelagics (Agostini & Bakun, 2002; Mercado *et al.,* 2013). The main commercial species are *E. encrasicolus* and *S. pilchardus*. Given the markedly multi-species nature of GSA 01, their abundance compared with the rest of the pelagic community was fairly low. Other pelagic species, such as *S. aurita, S. colias, T. mediterraneus, T. trachurus, Trachurus picturatus* and *B. boops*, are also found in GSA 01. The scarce anchovy and sardine stocks (Fig. 5, Table 1) and the fact that they exhibit a highly coastal behaviour, due to local topography and water circulation, often affect survey catchability. The sardine biomass fluctuated widely in GSA 01, rising from 2010, peaking in 2018 (Fig. 3) and plummeting in 2019. The anchovy biomass (Fig. 2) showed a significant upward trend (p-value: 0.04618, $R^2 = 0.3724$). These wide fluctuations make annual surveys essential to monitor stock status. Moreover, the abundance estimates are used as tuning indices in stock assessment models (STECF, 2017; GFCM WGSASP, 2019).

In GSA 06 - *Northern Spain*, the northernmost part is characterized by a narrow continental shelf and numerous underwater canyons, whereas the southernmost part has an extensive continental shelf (more than 33 nm in its widest area) that is conditioned by the Ebro River. GSA 06 is dominated by two well-defined, density-driven currents. In the northern part, a frontal jet flows in south-western direction along the slope (Castellón *et al.,* 1990). In the south, off the Gulf of Valencia, part of the flow continues southward, along the Spanish coast. Another branch bifurcates and recirculates cyclonically to feed the return Balearic Current along the northern Balearic Island shelf (Pinot *et al.,* 2002). The largest amount of nutrients is supplied by the Ebro River. This area of the Spanish Mediterranean provides an essential habitat for small pelagics (Bellido *et al.,* 2008, Tugores *et al.,* 2010). The anchovy and sardine biomass is substantially higher than in the nearby GSA 01 (Figs 2 and 3). The anchovy biomass showed a significant (p-value: 0.001857, R^2 = 0.6774) rising trend (Fig. 2); the sardine biomass was lower and lowest in 2014 and 2019 (Fig. 3). The estimates for the two species are used for tuning stock assessment models (STECF, 2017; GFCM WGSASP, 2019).

The *Gulf of Lions* (GSA 07) is characterized by a large continental shelf measuring ~ 20,400 km² (Millot, 1990) and is one of the most productive areas in the Mediterranean, due to a combination of shallow waters, depths up to 200 m, Rhône River discharges (Fig. 5) and coastal upwelling driven by northerly winds (Minas & Minas, 1989). Significant changes have recently affected its pelagic ecosystem; in particular, decreasing nutrient concentrations from east to west and from coastal to deeper waters (Bănaru *et al.,* 2013a, b) might exert an influence on the pelagic community. In the first years of the series (Figs 2 and 3), the sardine and anchovy biomass estimates were high, whereas the sprat biomass was low (Fig. 4). In recent years, the sprat biomass has been increasing significantly (Fig. 4, p-value: 0.000011, R^2 = 0.5598); in contrast, anchovy and sardine, traditionally the most important species in terms of biomass and landings (~ 50%), are no longer profitable due to a decline in specimen size and weight, for which market demand is limited. The anchovy and sardine stock assessment model in GSA 07 uses the MEDIAS biomass indices (GFCM WGSASP, 2019).

GSAs 09 and 10 (respectively *Tyrrhenian Sea and Ligurian Sea*) differ in terms of water circulation and environmental features. In the Tyrrhenian Sea, mixing of surface and deep layers by wind-driven turbulence enriches the upper layer, providing a relatively higher nutrient concentration compared with the Mediterranean basin (Nair *et al.,* 1992; Nezlin *et al.,* 2004). The Ligurian Sea is significantly colder than the Tyrrhenian Sea and is characterized by a large-scale cyclonic circulation affecting all water masses (Astraldi & Gasparini, 1992) and the biomass and spatial distribution of small pelagics (Figs 2 and 3). In GSA 10, the anchovy biomass was higher than that of sardine throughout the time series and displayed roughly the same trend (Figs 2 and 3). These estimates are used as tuning indices in surplus production stock assessment models in both areas (STECF, 2017; GFCM WGSASP, 2019).

Central Mediterranean

GSA 16 - *Strait of Sicily* is characterized by permanent coastal upwelling and a complex circulation of surface water, dominated by highly variable mesoscale processes (Bonanno *et al.,* 2014b). The abundance and distribution of small pelagics is driven by the strength of the upwelling. Here, the anchovy and sardine biomass estimates exhibited rapid fluctuations with high interannual variability (Figs 2 and 3). The sardine biomass (Fig. 3) showed a significant decreasing trend (p-value: 0.04072, R^2 = 0.1931). In this area, the stock assessment models of both species use MEDIAS biomass estimates as tuning indices (STECF, 2017; GFCM WGSASP, 2019).

Adriatic Sea

GSA 17 - *Northern Adriatic Sea* is the widest continental shelf in the Mediterranean Sea (Pinardi *et al.,* 2006), extending for about 500 km along the longitudinal axis of the basin and presents a high diversity of environmental conditions. Being a continental basin, the circulation and water masses are strongly influenced by the atmospheric forcing (rivers runoff, surface marine circulation, wind-induced upwelling) (Orlić *et al.,* 1992, 1994, Morello & Arneri, 2009). The geomorphological differences between the western and the eastern side of the basin, which are characterized respectively by shallow areas and generally sandy coasts with numerous rivers and by deeper areas and rocky coasts with few rivers (Artegiani *et al.,* 1997; Marini *et al.,* 2008), go some way towards explaining the much higher nutrient inputs and consequently the higher biomass of small pelagics that characterize the western compared with the eastern side (Fig. 5).

The western side of GSA 17 - *North-western Adriatic Sea* is characterized by high productivity due to strong runoff from the Po River and the other northern Italian rivers. The Po River inputs have been estimated to contribute about 20% of the whole Mediterranean river runoff (Hopkins, 1992). Small pelagic fish species are mainly concentrated in the northernmost shallow area (depth < 50 m), where the high productivity is related to river runoff (Fig. 5). Going southwards, their density decreases and they show a coastal distribution. The anchovy biomass (Fig. 2) is characterized by wide fluctuations. It collapsed in 1986 and remained very low until the late 1990s (Azzali *et al.,* 2002), then a significant increasing trend has been recorded since the beginning of the series (p-value: 0.01141, R^2 = 0.1569). The sardine biomass was low in 1976-1980 and subsequently increased up to the mid-1990s (Fig. 3). The decline of the anchovy population in 1986-1990 coincided with the low sardine biomass. Since 2015, the sardine biomass has undergone another sharp decline. In the early part of the series, sprat showed wide fluctuations, with high peaks (Fig. 4) followed by very low flats. Wide fluctuations have also been detected in the past few years.

On the eastern side of GSA 17 - *North-eastern Adriatic Sea*, the largest concentrations of small pelagic fish are found in the inner sea, among the islands and in association to the coast (Fig. 5). The anchovy, sardine and sprat biomass from 2013 to 2019 were estimated by the MEDIAS survey carried out east of the midline. Hydroacoustic data were recorded along transects perpendicular to the midline except near the islands, where they were adapted to the complex geomorphology of the coast (Artegiani *et al.,* 1997). The available estimates indicate that in most years sardine was much more abundant than anchovy (Figs. 2, 3; Table 1). The anchovy biomass (Fig.

2), showed limited fluctuations in the first years, with a peak in 2018 followed by a sharp decline in 2019. The same was true of sardine (Fig. 3) which peaked in 2018 and fell to intermediate values in 2019. The biomass of sprat, a species of low commercial value in the Adriatic, fluctuated widely with the lowest value in 2017 and the highest in 2019 (Fig. 4).

In GSA 18 - *South-western Adriatic Sea*, the water exchange with the rest of the Mediterranean takes place through the Otranto Strait, which has a sill at 800 m (Morello & Arneri, 2009; Specchiulli *et al.,* 2016). The bathymetry of the southern sub-basin (GSA 18) is characterized by a wide depression about 1200 m in depth. The spatial distribution of small pelagics is mainly coastal (Fig. 5). Abundance is especially high in the Manfredonia Gulf, characterized by shallow waters significant freshwater inputs. The biomass estimates (Figs 2 and 3) were lower than in GSA 17, which is more productive. The low anchovy biomass recorded at the beginning of the series was followed by broad fluctuations. In the past few years, values have settled around the average of the time series. The sardine biomass estimates presented wide fluctuations.

In GSAs 17 and 18, the acoustic abundance indices are used for tuning stock assessment models, which in recent years have been extended to cover the whole Adriatic Sea (see for instance Carpi *et al.,* 2015; Angelini *et al.,* 2017a, b; STECF, 2017; GFCM WGSASP, 2020).

Eastern Mediterranean

The *Eastern Ionian Sea* (GSA 20) is characterized by a complex topography including closed gulfs (*e.g.* Ambracian Gulf, Corinthiakos Gulf) and semi-closed basins (e.g., Kerkyraikos and Patraikos Gulfs). The Patraikos Gulf is connected to an outer basin with a wide continental shelf surrounded by several islands (Fig. 5). The Corinthiakos Gulf is a closed basin characterized by deep waters (up to 600 m depth) and a very narrow continental shelf. The Eastern Ionian Sea is generally a low productivity area with the exception of the Ambracian Gulf and the Patraikos Gulf. The latter receives surface waters from the Ionian Sea, while its bottom layer is influenced by the Corinthiakos Gulf water mass from the east through a narrow (2.5 km) and shallow (50 m) strait (Friligos, 1987). Moreover, the Patraikos Gulf water mass is influenced by freshwater inputs from small rivers flowing to its north and south (Ramfos *et al.,* 2006). In the Eastern Ionian Sea, more than 80% and 50% of the anchovy and sardine biomass, respectively, is found in the Ambracian Gulf (Fig. 5). The north-eastern part of the Gulf is characterized by poor water circulation and a sub-surface anoxic layer serving as a boundary for the vertical distribution of pelagic fish schools. MEDIAS data are available since 2013. The biomass estimates are much lower than in GSA 22, especially for sardine (Fig. 3). In GSA 20, the biomass estimates of both species show high interannual variability, with the anchovy estimates being consistently higher than those of sardine (Figs 2 and 3). The anchovy and sardine stock assessment model in GSA 20 uses the MEDIAS biomass indices (GFCM WGSASP, 2021).

The *North Aegean Sea* (GSA 22) is characterized by high hydrological complexity, mostly related to the Black Sea water (BSW), which enters the Aegean Sea through the Dardanelles Strait. The overall circulation is mainly determined by the Limnos-Imvros stream, which carries waters of Black Sea origin onto the Samothraki plateau (Somarakis & Nikolioudakis, 2007; Giannoulaki *et al.,* 2014), thus generating a permanent anticyclonic system. The outflow of BSW enhances local productivity and its advection in the North Aegean Sea determines a high hydrological and biological complexity (Somarakis & Nikolioudakis, 2007). Such complexity is compounded by the presence of several large rivers flowing into semi-closed basins like the Thermaikos Gulf, which enhance local productivity. Both anchovy and sardine biomass estimates exhibited high interannual variability (Figs 2 and 3). In the 1990s, the sardine biomass vastly exceeded the present estimates, although the lack of data for 2007, 2009-2012, 2015, 2017 and 2018 in GSA 22 prevents computing a trend. The estimates of the two species are used for tuning stock assessment models: as biomass indices in surplus models and as age structure indices in analytical stock assessment models (e.g., Antonakakis *et al.,* 2011; Giannoulaki *et al.,* 2014; STECF, 2017; GFCM WGSASP, 2019, 2021). Biomass changes from year to year seem to affect the spatial aggregations of both species, as highlighted by the estimated geostatistical and spatial indicators (Barra *et al.,* 2015).

Contribution of the MEDIAS action to ecosystem knowledge and the Ecosystem Approach to Management

Though largely collected for stock assessment purposes, the hydroacoustic data, and the complementary data provided by the surveys, can supply monitoring information on population abundance and biomass, spatial distribution and predator–prey relationships in the Mediterranean, thus contributing to achieve the EBM (Trenkel *et al.,* 2011). An ecosystem approach to data collection can support the assessment of the state of the marine environment in line with the objectives of the EU Marine Strategy Framework Directive (MSFD, 2008/56/EC).

Different ecosystem indicators can be computed based on the data consistently collected during the hydroacoustic surveys (Table 2; MEDIAS, 2019). Besides population size, biomass and abundance at age and size, which are estimated each year, they include the recruitment index and indices regarding habitats and hydrological conditions as well as basic information on spatial distribution, which could be used to monitor changes in species distribution over time (Trenkel *et al.,* 2011). The relationship between stock abundance and spatial distribution provides information on any changes in fisheries catchability in relation to stock size (Petitgas, 1998; Barange *et al.,* 2009); in particular, changes like habitat shrinkage may result in increased catchability due to re-

Table 2. Ecosystem Indicators based on data regularly collected and analysed in the MEDIAS acoustic surveys.

Good Environmental Status indicators	Spatial/ temporal strata	Spatial strata	GSA				
			Acoustic survey				
		Time periods	Season (summer/autumn depending on the area)				
	Taxonomic levels	Community	Pelagic fish (species composition, occurrence in pelagic hauls)				
		Target species	Adult	Anchovy			
				Sardine (Mediterranean Sea)			
				Sprat (Black Sea)			
	Indicators	Biodiversity	Species	Population size	Acoustic estimates	Total biomass and abundance estimates for the target species	
						Estimation error (CV) (as agreed based on a shared estimation procedure, see ToRs)	
				Population condition	Biomass and abundance estimate per size/age	Anchovy, sardine and sprat (Black Sea)	
					Recruitment index	Sardine (*i.e.* number at age 0 of the population based on summer surveys)	
				Habitats	Habitat condition	Hydrological condition	Temperature (*i.e.* SST: average at 10 m estimated as the interpolated mean value for the whole area)
							Salinity (*i.e.* SSS: average at 10 m estimated as the interpolated mean value for the whole area)
			Community	Fish community condition	Community synthesis	Total pelagic fish NASC	
					Species composition (*i.e.* percentage in terms of weight of pelagic trawls *per* hour)		
			Age and size distribution	95% percentile of the population length distribution for the target species			
				Proportion of fish larger than L_{50} (length at first maturity estimated based on collected data or defined based on literature data)			

duction of the area where a species is distributed.

Important complementary information could be collected during the hydroacoustic surveys. Such data include for instance zooplankton and ichthyoplankton samples, environmental parameters and information on the presence of marine mammals and seabirds. Useful additional information – which is collected depending on fund availability – has been reported in separate publications (*e.g.* comb jelly fish distribution: Siapatis *et al.,* 2008; ichthyoplankton: Somarakis *et al.,* 2004; Somarakis & Nikolioudakis, 2007; Schismenou *et al.,* 2008; Basilone *et al.,* 2013; Malavolti *et al.,* 2018; Somarakis *et al.,* 2019; marine mammals: Giannoulaki *et al.,* 2017a; mesozooplankton: Ventero *et al.,* 2019, 2020; mesopelagic fish distribution: Kapelonis *et al.,* 2019a). The most recent examples include the use of hydroacoustic data collected in GSA 01 to provide secondary production indicators (Ventero *et al.,* 2020).

Plankton samples collected during the hydroacoustic surveys can also supply information on the ichthyoplankton fraction, thus providing a more exhaustive knowledge of spawning (from collected eggs) and nursery areas (based on collected larvae). This is especially true of anchovy, for which the survey period allows gathering such data (Somarakis *et al.,* 2004; Schismenou *et al.,* 2008; Basilone *et al.,* 2013; Giannoulaki *et al.,* 2013; Malavolti *et al.,* 2018). Plankton samples would also allow exploring new management scenarios in the Mediterranean Sea, including local closures that take into account spawning and nursery areas. Plankton analysis can also provide additional information on pelagic ecosystem structure and function.

In addition, hydroacoustic data obtained during the standard MEDIAS monitoring surveys can provide information on the abundance and distribution of mesopelagic fish assemblages (Kapelonis *et al.,* 2019a, b). In fact, besides being a potential new fishery resource, such assemblages are important constituents of the Mediterranean food web that have recently attracted the scientists' attention (ICES, 2019).

Conclusions and future prospects of hydroacoustic surveys

A major improvement in the standardization of the national hydroacoustic surveys conducted by Mediterranean States has been the harmonization of the MEDIAS protocol – which has been pursued since 2009 by the MEDIAS Steering Committee – in the framework of the EU DCR (MEDIAS, 2008). However, harmonization is a dynamic process; accordingly, every year the protocol is modified to achieve an even greater harmonization and modernization of the mandatory surveys (MEDIAS, 2019).

In each GSA, the survey design and the inter-transect distance have been optimized in relation to the spatial characteristics of small pelagic fish aggregations and survey duration. Among the issues agreed by participants are hydroacoustic data sampling and analytical parameters such as the minimum sampling depth enabling capture of the spatial distribution of small coastal pelagic fish like sardine and a common workflow for hydroacoustic data processing. The need for a shared database to store the survey data has also been recognized.

Collaboration among the hydroacoustic groups participating in the MEDIAS surveys has been promoted with regard to the spatial distribution of the target species (*e.g.* Giannoulaki *et al.,* 2011, 2013; Tugores *et al.,* 2011; Brosset *et al.,* 2017), habitat selection (e.g., Bonanno *et al.,* 2014a) and methodological aspects like pelagic haul sampling (e.g., Machias *et al.,* 2013).

In addition, collaboration has been promoted with the ICES Working Group on Acoustic and Egg Surveys (ICES WGACEGG) – the ICES working group on anchovy and sardine hydroacoustic surveys in the Atlantic region – and with the scientists working on hydroacoustics in the Black Sea and the South Mediterranean States, by inviting them to participation in the MEDIAS Steering Committee annual meeting.

Information for anchovy and sardine stock assessment is provided for each GSA also based on the results of hydroacoustic surveys conducted according to the common MEDIAS protocol in non-EU areas, as an extension of the MEDIAS action. Hydroacoustic estimates are regularly used for small pelagic fish stock assessment by the FAO GFCM and EU STECF working groups (e.g., GFCM WGSASP, 2019, 2020, 2021).

Given the importance of the complementary information that can be gathered during the hydroacoustic surveys, the MEDIAS protocol could be extended to include continuous and coordinated sampling for current and future DCF requirements. Such complementary information can enhance ecosystem knowledge and contribute to the EBM. Plankton sampling can provide useful information on the pelagic ecosystem, thus contributing to the ecosystem approach, and improve hydroacoustic data analysis by providing information on the main plankton taxonomic classes or hydroacoustic categories from biological sampling. These data would also allow studying the spawning and nursery areas of the MEDIAS target species in greater detail.

The MEDIAS activities are likely to evolve to an integrated monitoring of the pelagic ecosystem of the Mediterranean Sea. In all GSAs, the surveys have followed an ecosystem approach by monitoring, depending on vessel time availability, additional information on hydrology, phytoplankton, zooplankton, birds and mammals besides assessing fish stocks. The strong potential of fisheries hydroacoustic surveys for ecosystem monitoring has also been demonstrated in other areas, like the Bay of Biscay by the French PELGAS program (Trenkel *et al.,* 2011; Baudrier *et al.,* 2018; Doray *et al.,* 2018). In this regard, in several regions including the Mediterranean, hydroacoustic, net and other oceanographic sampling approaches have already been combined to assess how oceanographic conditions influence pelagic ecosystems and the fish that inhabit them (Giannoulaki *et al.,* 2011, 2013, 2017b; Tugores *et al.,* 2011; Brosset *et al.,* 2017; Ben Abdallah *et al.,* 2018; Doray *et al.,* 2018; Zgozi *et al.,* 2018).

Despite the ongoing work to improve the shared protocol, there are some outstanding issues that need to be addressed; these include the available frequencies *per* area, the catchability of all pelagic species, the need for standardized echogram scrutinization and intercalibration of the research vessels. Furthermore, the common MEDIAS database should finally be developed and adopted. A shared TS equation for anchovy is needed after the one for sardine has been estimated in the framework of the AcousMed project (Anonymous, 2012). A common TS for the MEDIAS target species would allow obtaining comparable biomass data in the different Mediterranean GSAs, since the species share the same acoustic response characteristics irrespective of oceanographic and physical differences. Standardization and harmonization of hydroacoustic biomass evaluations among EU Mediterranean States would provide consistent information for management decisions and valuable inputs for the assessment of international stocks.

Information on the state of small pelagics is becoming increasingly crucial in the Mediterranean Sea, given the overexploitation of most pelagic fish stocks in the region. Certain areas are not yet covered, like the Western Ionian Sea (GSA 19), Sardinia (GSA 11) and the Balearic Islands (GSA 05).

The future of the hydroacoustic surveys in the Mediterranean will be driven by new technologies, such as sonar systems to study fish school shapes and broadband systems to study TS. Multibeam systems and directional sonars (e.g., Trenkel *et al.,* 2008, Korneliussen *et al.,* 2009) will improve our knowledge of the three-dimensional shape and spatial distribution of schools and enhance our ability to identify fish that are not properly captured by hydroacoustic surveys, due to their reaction to sound and the survey vessel. From a methodological viewpoint, technological advances will also allow employing a wider range of frequencies in all GSAs. The overarching aim is to apply the same multifrequency method, or use the echo sounder in broadband mode in hydroacoustic data processing, to optimize the discrimination of pelagic organisms and obtain better results in single-target analyses aimed at estimating the TS of the species of interest.

Further progress could be made by acquiring new EU research vessels equipped with the most advanced hydroacoustic technology, which would enable the MEDIAS groups to carry out their work more rapidly and to start data processing at sea, immediately after acquisition, thus reducing the time required to produce the annual assessment results. Notably, vessels of adequate size could also operate in a wider range of sea conditions. New challenges include the monitoring of zooplankton and other species, like semi-demersal species such as *Trachurus* spp. (Palermino *et al.,* 2021) and Lessepsian species recently introduced into the Mediterranean, like *Etrumeus golanii.*

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Supplementary Data

The following supplementary information is available online for the article:

Figure S1: Acoustic transects in targeted survey areas conducted in the Adriatic Sea in 1968-1972. (A) Kaštela Bay; (B) areas near Vis and Biševo islands; (C) Hvar Island-Neretva Channel and (D) Palagruža Sill (Kačić, 1968, 1969, 1972a, b; Grubišić et al., 1974; Vučetić & Kačić, 1973).
Figure S2: Design of the pilot acoustic survey conducted in the Adriatic Sea in 1975 (Azzali, 1977).
Figure S3: Acoustic equipment mounted onboard the Italian R/V *S. Salvatore Lo Bianco* in the 1970's and 1980's. Simrad QM-MK II echo integrator and associated computer (top left). A 38 kHz transducer in "wide" bandwidth configuration was used. A Simrad SL sonar (top right). Echograms of small sardine aggregations (right) printed on wet (top) and/or dry paper tape and relevant echo integrations (left). Time interval 9:46 - 10:04.
Figure S4: Acoustic equipment used in the 1960's, 1970's and 1980's.
Table S1. List of Mediterranean acoustic surveys from 1962 to 2019, by Country.