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Spatial and temporal dynamics of trawl fishing activities in the Northern and Central Adriatic Sea (GSA 17) analysed by using Automatic Identification System (AIS) data

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General abstract

The primary aim of this PhD project was to improve the knowledge about the spatio-temporal dynamics of trawl fishing activities in the Northern and Central Adriatic Sea (GSA17). This area has been recognised as one of the most exploited within the Mediterranean basin and for this reason the assessment of the fishing effort results to be an important element for the implementation of new management strategies. The use of Automatic Identification System (AIS) data, available for vessels with a length overall (LOA) over 15 m, played a key role for the investigation of this topic. Indeed, this system, conceived for navigation security reasons, provides high spatio-temporal resolution information about the fishing vessel distribution and activities. Considering the characteristics of the Adriatic fishing segments, and since the trawl fishery is one of the most negatively impacting fishing techniques, the entire study was focused on the trawl fleet, and in particular on Small and Large Bottom Otter Trawl, *Rapido* Trawl (a sort of beam trawl) and Mid-Water Pair Trawl. The main aims of this project are:

1. the evaluation of the fishing effort, estimated by using an innovative method considering the fishing tracks of the vessels and the swept area, in order to identify the main fishing grounds and the seasonal behaviour of the different fishing techniques;
2. the catches assessment on a spatial basis, associated with fishing effort and economic value in order to better understand the fishermen behaviours and the efficiency of the selected fishing segments;
3. the estimation of the carbon dioxide (CO_2) emissions, by using a bottom-up approach (AIS-based method), and the emissions associated with landing data in order to assess the impact produced to catches commercial species (kg CO_2 per kg landing).

Overall, this research project supplied new insights in a context of sustainable fishery management, providing useful information for the monitoring and the assessment of the trawl fishing activities in the Adriatic Sea.

Introduction and study framework

Marine ecosystems produce several ecosystem services, with high economic and social relevance, essential in providing benefits to human well-being, for instance in terms of food security (Costanza et al., 1997; McClanahan et al., 2015). In this context, fishery is a key food-producing sector that must guarantee food and nutrition for the growing human population in the future (FAO, 2018). However, due to the rapid increase in the demand of seafood, especially in the last decades, marine living resources have become more vulnerable (FAO, 2018). Indeed, fishing activities have direct and indirect negative effects on the entire ecosystem, including changes of the habitat's structures and of trophic web, which caused loss on biodiversity and alteration of the ecosystem functionality (Jennings and Kaiser, 1998; Jackson et al., 2001; Johnson et al., 2015; Mangano et al., 2015, 2017; Marra et al., 2016), and Greenhouse Gases (GHG) emissions (Parker et al., 2018). Indeed, together with the fishing impacts on the marine communities, also the GHG emissions represent an emerging issue, considering the global effort to maintain the temperature rise well below the 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5ºC (IPCC, 2018).

Since the 1950s fishing catches grown more and more up to the early 1990s, when the world production reached a steady value of around 80 tonnes (FAO, 2018) as consequences of the rapid decrease of new fishing grounds, indicating a global limit to the growth of the fishery sector and highlighting the urgent need to reach a sustainable fishery (Swartz et al., 2010). Indeed, since many fish stocks have been excessively exploited due to non-selective and unsustainable fisheries (Colloca et al., 2013; Vasilakopoulos et al., 2014; STECF, 2016; Russo et al., 2019), developed countries started to improve the management of their fishery sector with the aim to exploit the fish stocks at a biologically sustainable levels (FAO, 2018). In particular, the European Union (EU) developed different directives with the aim to improve the fishery management in order to reverse the decline of fish stocks and ensure the sustainable exploitation of fishery resources. Indeed, in the EU the fishery activities represent a key sector with 4.5 million tonnes of fishes landed in 2017, an economic value of 7.3 billion euro and about 178000 employment (Agriculture, forestry and fishery statistics, 2018).

The most important instrument used to manage the fishing activities in the European Union is the Common Fisheries Policy (CFP; 2013/1380/EC), whose primary goal is to guarantee a sustainable fishery, as well as income and stable jobs. During the years the CFP was reformed establishing a series of actions, such as the implementation of multiannual plans, the adoption of conservation measures and the application of precautionary principles. Moreover, the current version of the CFP, which came into force on 1st of January 2014, increased the focus on regionalization contributing to the implementation of the process at local level and adapting the governance structures to the specific needs of the country seas. Together with the CFP, the EU developed others important directives related with the fishery management, and in particular the Marine Strategy Framework Directive (MSFD; 2008/56/EC), aiming to achieve a Good Environmental Status (GES) of the European marine waters by 2020, and the Maritime Spatial Planning (MSP; 2014/89/EU), for the promotion of the sustainability of the economic activities in the sea. These directives stress the importance to implement the utilization of an Ecosystem-Based Approach to the fishery management, as well as an integrated approach at regional and sub-regional level (Burgt et al., 2017; Libralato et al., 2018).

Despite the enforcement of these EU directives, their application in the Mediterranean Sea, characterized by multi-species and multi-gears fishing activities, resulted very challenging, due to the complexity of the ecological, economic, social and political differences within this basin (Carpi et al., 2017; Libralato et al., 2018). To date, the development of an effective fishery management plan is more and more needed in order to reduce the unsustainable exploitation and move towards a healthy and more resilient ecosystem (Bastardie et al., 2017).

Management strategies and measures applied to regulate, manage and protect the marine environment require a long-term monitoring to test their effectiveness (Pranovi et al., 2015; Sciberras et al., 2015). In this context, the improvement of knowledge, useful to develop efficient fishery management strategies, is fundamental in order to reach a sustainable fishery, on environmental, economic and social basis, ensuring a productive and healthy ecosystem, and ensure the availability of the marine resources for the future generations. Moreover, under the requirement of the 2030 Agenda for Sustainable Development, which established 17 Sustainable Development Goals (SDGs), and in particular with the SDG 14 "*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*", the management of fishing activities needs to be constantly monitored and new policies should be integrated and implemented. At the same time, considering the spatial connectivity and movements of the stocks, the management of fishing activities are more challenging in areas where different countries shared the same resources (Bastardie et al., 2017; Carpi et al., 2017). In this context, the Northern and Central Adriatic Sea (GSA 17), enclosed among Italy, Croatia and Slovenia, represent a good case study to analyse different aspect of fishery management. Moreover, this area is characterized by high level of productivity, mainly due to the presence of river estuaries, which makes this basin highly exploited (Barausse et al., 2009; Pranovi et al., 2015; Fortibuoni et al., 2017). In this basin, where Italian, Croatian and Slovenian fleets cohabit, the overexploitation of the fishery resources was already pointed out (*e.g.*, Colloca et al., 2013; 2017; Fortibuoni et al., 2017). As previously specified, the fishing activities in the Adriatic Sea are multi-species and multi-gears, and this make even more challenging the assessment and the monitoring of them. Considering also the presence of different protected areas, such as nursery areas (*e.g.*, Pomo Pit) or Site of Community Importance (SCI), as well as the presence of several important species (*e.g.*, anchovies, sardines, common soles, cuttlefish, Norway lobster, etc…), this basin needs to be widely managed and studied. Currently, several management measures are enforced in the Adriatic basin, such as fishing restrictions (*e.g.*, control of fishing capacity), catch limits (*e.g.*, total allowable catch for the bluefin tuna and swordfish), the reduction of fishing effort, technical measures (*e.g.*, mesh size of the net, minimum landing size for several species), the establishment of temporal/permanent closures (*e.g.*, the ban of trawling activities within 3 nm of the Italian coast, established with the Council Regulation 1967/2006/EC, and the ban of trawling activities for biological recovery purposes). Additionally, the Adriatic Sea is object of specific regulations, such as the periodical ban of demersal activities in the Jabuka/Pomo Pit area, or the recent multiannual plan acts to regulate the fishery of small pelagic fishes, which are one of the main target species in the GSA17. However, the effectiveness of these measures needs to be assessed by monitoring the fishing activities in space and time, and improving their knowledge, key elements for both researchers and policymakers. Moreover, analysing the fishing activities on basis of different fishing segments and focusing the research at regional scale, which importance was already highlighted by the new CFP (2013/1380/EC), allowed a more accurate assessment of the trawl fishing activities. In the last years, many efforts have been devoted to manage the fishing activities, and the utilization of specific tools, such as Vessel Monitoring System (VMS; Lee et al., 2010; Russo et al., 2011a, 2011b, 2016; Lambert et al., 2012; Campbell et al., 2014; Mangano et al., 2014, 2015) and Automatic Identification System (AIS; Natale et al., 2015; Russo et al., 2016; Ferrà et al., 2018), has become more and more relevant. However, even if the VMS was introduced by the European Union for monitoring the fishing activities, it presents some limitations, such as the low frequency of the signals and in some cases the difficulty to gain the data (Ferrà et al., 2018). On the other side, AIS, designed primarily as navigational aid to avoid vessel collisions, provides useful information with high temporal resolution and could represents a valid tool for the assessment and the monitoring of the fishing vessels activities. Therefore, despite possible criticalities, such as the spatial coverage and the size of the vessel (length overall [LOA] > 15m) equipped with this system, the use of AIS data for scientific and managing purposes is becoming increasingly common in the scientific community (Natale et al., 2015; Vespe et al., 2016; Ferrà et al., 2018;

Shepperson et al., 2018). In the Northern and Central Adriatic Sea high level of coverage (75-100%) of the AIS data has been detected (Blue Hub[1]), ensuring an effective use of these data for fishery management purposes. However, it is worthwhile to notice that the AIS data analysed not considered a small portion of the South Eastern part of the GSA17, in the nearby of Montenegro, and therefore this area was not included in this project.

Previous works have already investigated the fishing activities in the Adriatic Sea under several aspect, such as fishing effort, species distribution and landing time series analysis (*e.g.*, Scarcella et al., 2014; Pranovi et al., 2015; Fortibuoni et al., 2017; Russo et al., 2019). However, the integrated and interdisciplinary use of AIS data to assess the fishing effort estimated as swept area, and in particular the association with landing data, economic value and GHG emissions, has never been performed in the Adriatic Sea.

Overall, this research project provided new insights in a context of sustainable fisheries management, making available useful information for the monitoring and the assessment of the trawl fishing activities in a focal area of the Mediterranean Sea.

In order to reach these purposes, three mains complementary studies have been developed:

1. Temporal and Spatial Patterns of Trawl Fishing Activities in the Adriatic Sea (Central Mediterranean Sea, GSA17).

The first objective of this research was the evaluation of the fishing effort, estimated by using an innovative method, recommended in 2015 by the International Council for the Exploration of the Sea (ICES) and to date still not widely adopted, that use the fishing vessels tracks, derived from the interpolation of AIS data, to estimate the swept area, in order to identify the main fishing grounds and the seasonal behaviour of the different trawl fishing segments. Differently from the nominal fishing effort, which can be considered a *proxy* of the real fishing effort, being generally a function of time (fishing days/hours) and of the total resources allocated to the fishing activities (*e.g.*, number of vessels and fishermen, engine power of the vessels, etc.; Pascoe and Robinson, 1996; McCluskey and Lewison, 2008), the fishing effort deriving from the swept area, although present some limitations, can be considered more realistic for the estimation of the exploitation degree.

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[1] https://bluehub.jrc.ec.europa.eu/mspPublic/ (last accessed September 2019)

2. Spatial distribution of trawl fishing catches integrated with income and fishing effort in the Northern Adriatic Sea (GSA17)

The second objective of the research was the catches assessment on a spatio-temporal basis, associated with fishing effort and economic value in order to better understand the fishermen behaviours and the efficiency of the selected fishing segments. This study assessed the fishing activities of the Northern Adriatic Sea (GSA17) by combining three dataset sources: landings, fishing effort and economic value. The assessment of catches on a spatio-temporal basis, associated with the fishing effort, represents one of the main challenges within the context of the implementation of the real Ecosystem Based Fishery Management (EBFM). The identification of the fishing grounds, on basis of the combination of the three cited above variables, allowed to determine the efficiency of the different areas and gears. Moreover, high-resolution maps of the main target species were carried out on seasonal basis, highlighting seasonal changes on their distribution, allowing a better explanation of the fishermen behaviour.

3. Estimation of carbon dioxide (CO_2) emissions in the Northern and Central Adriatic Sea (GSA 17)

The third objective of the research was the estimation of the carbon dioxide (CO_2) emissions caused by the trawl fleet in the Northern and Central Adriatic Sea. The impacts, expressed in terms of emissions produced to catch different commercial species (kg CO_2 per kg landing), were assessed by associating the CO_2 emissions with landing data related to the Chioggia trawl fleet (Northern Adriatic Sea). Specifically, a bottom-up approach (AIS-based method), considering the tracks of the fishing vessels to discriminate the time spent in fishing and navigation, essential information for the estimation of the fuel consumption, and to geographically localize the main emission areas, were carried out. Moreover, by coupling position data with landings per day per vessel it was possible to estimate the emission intensity (*i.e.*, emissions per unit of catches; *sensu* Gerber et al., 2013) for the main species groups (kg CO_2 per kg of catches).

Chapter 1. Temporal and Spatial Patterns of Trawl Fishing Activities in the Adriatic Sea (Central Mediterranean Sea, GSA17)

Abstract

Trawl fishing activities have occurred for centuries on large spatial scale in the entire Mediterranean Sea, and today are considered one of the main and widespread causes of anthropogenic disturbance and habitat alteration in the marine environment. In order to delineate when, where and how marine ecosystems have been perturbed and to implement real ecosystem-based management strategies, the identification and investigation of the spatial and temporal distribution of fishing effort and the fleet's dynamics play a key role. In this context, Geospatial Technologies such as the Automatic Identification System (AIS) could represent a useful tool. The aim of the present work is to reconstruct spatial and temporal patterns of the trawl fishing activities in the Northern and Central Adriatic Sea (GSA17), by using AIS data. High-resolution maps of fishing effort, both aggregated and disaggregated per fishing gears (small and large bottom otter trawl, *Rapido* trawl and mid-water pair trawl), allowed to identify the main fishing grounds and seasonal variations during the period 2015-2016. Moreover, the effects of the closure of the Pomo pit in terms of fishing effort redistribution, and the possible effects of the enlargement of the ban for the trawling activities to the 3-6 nm area, have been explored. Obtained results highlighted the importance to take into account the spatial and temporal dynamics of the fishing effort within the context of the implementation of a real ecosystem approach for fishery management purposes.

1.1 Introduction

The Northern and Central Adriatic Sea [Geographical Sub-Area, GSA 17], characterised by a wide continental shelf and eutrophic shallow waters, is well known to be intensively exploited by fishing activities (AdriaMed, 2004; Barausse et al., 2009; Pranovi et al., 2015; Fortibuoni et al., 2017). As consequence, many fish stocks in the area resulted overexploited (Colloca et al., 2013; Vasilakopoulos et al., 2014; Russo et al., 2019), due to non-selective and unsustainable fishery (STECF, 2016). In this context, the development of effective fishery management plans are needed in order to reduce the unsustainable exploitation of the fishery resources and move towards a healthy and more resilient ecosystem (Bastardie et al., 2017). Different management measures are currently used in the Mediterranean Sea, and therefore in the Adriatic basin, such as fishing and catch limits, technical measures and the establishment of temporal/permanent closures. In particular, it is worthwhile to mention the ban of trawling activities within 3 nm of the Italian coast, established with the Council Regulation 1967/2006/EC, and the ban of trawling activities for biological recovery purposes. Additionally, in the Adriatic Sea, the fishing activities were periodically banned in the Jabuka/Pomo Pit area, a recognised key nursery ground, especially for hake and Norway lobster. In particular, demersal fishery was interdicted from July 26th 2015 to July 26th 2016 (GU, 2015) a closure that was recommended also during the 41st session of the General Fisheries Council for the Mediterranean (GFCM, 2017) where the establishment of a Fisheries Restricted Area (FRA) in the Pomo Pit was endorsed.

In the last years, many efforts have been devoted to monitoring these activities using helpful and specific tools, such as Vessel Monitoring System (VMS; Lee et al., 2010; Russo et al., 2011a, 2011b, 2016; Lambert et al., 2012; Campbell et al., 2014; Mangano et al., 2014, 2015) and Automatic Identification System (AIS; Natale et al., 2015; Russo et al., 2016; Ferrà et al., 2018). The VMS, a satellite-based monitoring system providing several data to the fishery authorities at regular intervals (generally about 1-2 hours; Natale et al., 2015), was introduced by the European Union (EU), formerly for vessels over 15 m, and from 1 January 2012 also for vessels above 12 m (EC, 2009). Otherwise the AIS system, designed primarily as navigational aid to avoid vessel collisions, was introduced by the International Maritime Organization (IMO[2]), with the International Convention for the Safety of Life at Sea (SOLAS), for ships with 300 or more gross tonnage (GT) and all passenger ships. Nevertheless, with the entry in force of the European Directive 2011/15/EU, also fishing vessels have the obligation to install the AIS device (from May 2012 all vessels with a length of more than 24 m overall, from May 2013 all vessels above 18 m and from May 2014 all vessels above 15m). The AIS provides different kind of information with very high temporal resolution (few seconds): static information (*e.g.*, Maritime Mobile Service Identity [MMSI] number, IMO number, vessel name, International Radio Call Sign [IRCS], length and beam, type of ship), dynamic information (*e.g.*, ship's position, position time stamp in UTC, Course Over Ground) and voyager related information (*e.g.*, ship's draught, destination and estimated time of arrival [ETA], route plan). Despite the VMS were introduced specifically for the monitoring of fishing activities they have some limitations, such as long time between the transmission of two consecutive signals (low temporal resolution), as well as the difficulty to obtain the data, as already highlighted by other

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[2] http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx

authors (Shepperson et al., 2018; Ferrà et al., 2018). Hence, since the AIS data has a higher temporal resolution and are openly available to the public, the use of AIS data for scientific and managing purposes is quickly growing, in spite of possible criticalities, such as the spatial coverage, mainly in wide areas, and the size of the vessel (length overall [LOA] > 15m) equipped with this system (Ferrà et al., 2018; Shepperson et al., 2018).

Here we aim to improve the knowledge of the fishing activities in the Northern and Central Adriatic Sea, identifying the most exploited areas, the fishing grounds, as well as the annual and seasonal fishing behaviour of the Adriatic trawling fleet, both considering all the trawlers together and distinguishing by fishing gears. Moreover, the effectiveness of some current fishery management regulations has been tested and analysed. An innovative method, recommended in 2015 by the International Council for the Exploration of the Sea (ICES) and based on the swept area of the fishing vessels, has been used to assess the fishing effort. Indeed, differently from the nominal fishing effort, which can be considered a proxy of the real fishing effort, being generally a function of time (fishing days/hours) or of the total resources allocated to the fishing activities (*e.g.*, number of vessels and fishermen, engine power of the vessels, etc.; Pascoe and Robinson, 1996; McCluskey and Lewison, 2008), the fishing effort derived from the swept area, although present some limitations, can be considered more realistic for the estimation of the exploitation degree. Moreover, even if many authors had estimated the fishing effort using predominantly VMS data and different methods, such as the point summation (Mills et al., 2007; Lee et al., 2010; Mangano et al., 2014, 2015) and the interpolation (Mills et al., 2007; Hintzen et al., 2010; Pitcher et al., 2016), our approach has permitted to obtain a more reliable tracking of the fishing activities, being the AIS signals based on the transmission of very high frequency (VHF) radio signals. A similar approach was used by Ferrà et al. (2018) to map the fishing activities in the Mediterranean Sea, but only in terms of hauling length (km) and not of swept area (km^2).

1.2 Materials and Methods

1.2.1 Study area and fishing activities

The Northern Adriatic Sea is characterized by eutrophic shallow water and an extended continental shelf (average depth of 35 m), which is the widest of the Mediterranean Sea, while the Central basin is deeper, reaching 270 m of depth in the Pomo/Jabuka Pit. Moreover, the Adriatic Sea can be sub-divided into the eastern side, deeper and rocky, and the western side, that is mostly shallow, sandy and with the presence of many river outlets affecting the seawater circulation. The latter circulation is cyclonic with two main currents: the eastern and the western. The first one flew northwards along the eastern coast with the presence of three gyres, of which the northern one is influenced by strong winds (*e.g.*, Bora) and freshwater input (mainly coming from the Po River). This gyre creates the western current, which flow southwards along the Italian coasts carrying large amount of nutrients. Due to the high presence of nutrients, coming from rivers discharge, the GSA 17 is recognised as one of the most productive areas of the entire Mediterranean Sea, and consequently one of the most exploited European basins (Campanelli et al., 2011; Grati et al., 2013).

The studied area covered 74965 km^2 and referred to 3 different countries, Croatia (39946 km^2), Italy (34806 km^2) and Slovenia (213 km^2; **Figure 1.1**).

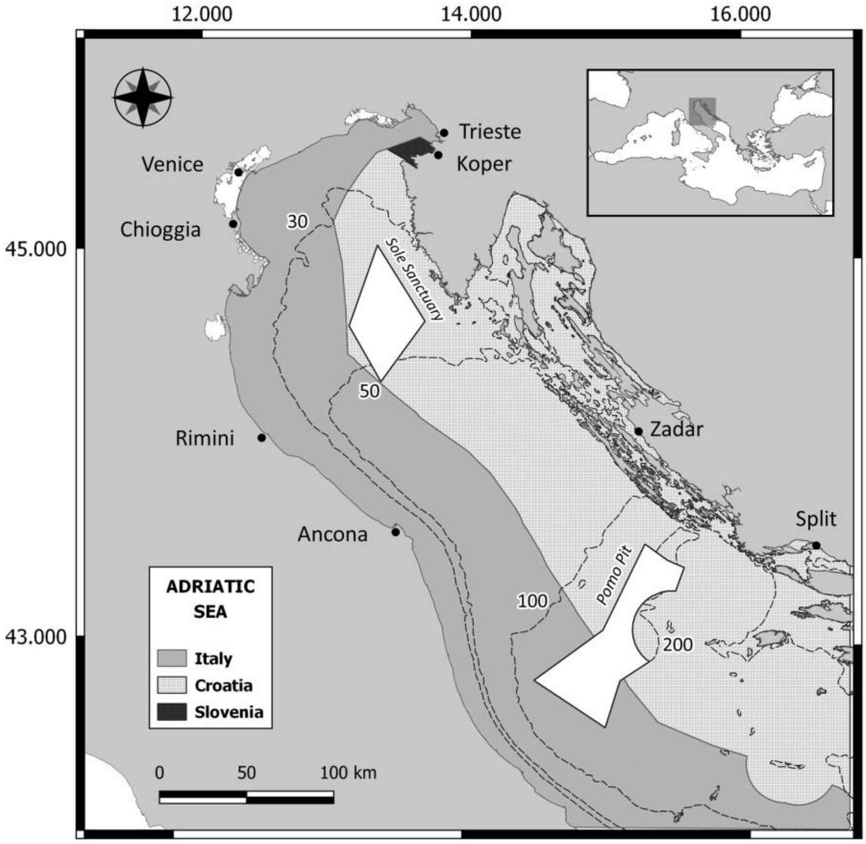

Figure 1.1. Northern and Central Adriatic Sea (GSA 17)

The analyses were focused on towed fishing gears (trawling), analysing different fishing segments: Small (LOA <18m) and Large (LOA >18m) Bottom Otter Trawls (SOTB and LOTB, respectively), *Rapido* (RAP), a sort of Beam Trawl, and Midwater Pair Trawl (PTM, also called *Volante*). These gears represent the largest portion of the Adriatic trawling fleet and are mostly constituted by Italian (~ 90%), Croatian (~ 10%) and Slovenian (< 1%) trawlers (**Table 1.1**).

Being the AIS mandatory only for vessels with LOA > 15 m, smaller Adriatic trawlers (about 435 OTB, 18 RAP and 20 PTM; data extrapolated from the Data Collection Framework – European Commission - STECF), were not considered in this work.

Table 1.1. Number of vessels of the Adriatic fleet grouped per gears (Large Bottom Otter Trawl-LOTB, Small Bottom Otter Trawl-SOTB, Mid-water Pair Trawl-PTM, *Rapido*-RAP) and nationality (Italian-ITA, Croatian-HRV and Slovenian-SLV).

			2015			**2016**	
Fishing gear	**LOA class (m)**	**ITA**	**HRV**	**SLV**	**ITA**	**HRV**	**SLV**
SOTB	**15 - 18**	110	31	2	121	30	2
LOTB	**18 - 24**	214	32	0	208	26	0
	> 24	57	9	0	53	9	0
RAP	**15 - 18**	7	0	0	7	0	0
	18 - 24	35	0	0	36	0	0
	> 24	27	0	0	27	0	0
PTM	**15 - 18**	23	0	0	23	0	0
	18 - 24	29	0	0	31	0	0
	> 24	42	0	0	44	0	0
National Fleet	**> 15**	**544**	**72**	**2**	**550**	**65**	**2**
GSA17 Fleet	**> 15**		**618**			**617**	

1.2.2 AIS data

The AIS raw data analysed in this study were provided by the Italian Coast Guard (ITC and Traffic Monitoring Department – Rome) and consist of around 922 million positions released by Adriatic fishing trawlers, operating in the GSA17 between January 2015 and December 2016. Position data (latitude and longitude), speed, time (Unix time) and the MMSI were used to analyse the fishing activities of 618 and 617 vessels for 2015 and 2016, respectively. In order to identify each fishing vessel, the International Radio Call Sign (IRCS), the ship's name and the MMSI number were used. First, the IRCS and the ship's name, reported in the AIS data, were linked to the EU Fishing Fleet's Register[3], which provides technical information about the vessels (*e.g.*, length overall [LOA], gross tonnage [GT], primary and secondary gears). Nevertheless, in some case (*e.g.*, erroneous IRCS or misspelled names) the Marine Traffic website[4] was used to identify the vessels thought the MMSI. Moreover, according to Natale et al. (2015), the speed frequency distribution was used for a more accurate identification of the

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[3] http://ec.europa.eu/fisheries/fleet/index.cfm

[4] https://www.marinetraffic.com/

fishing gears.

1.2.3 Data analysis

The whole dataset was stored into a data warehouse, a dedicated collection of subject-oriented, integrated, non-volatile and time-variant data. The data have been pre-aggregated for analytical purposes and implemented in a PostgreSQL[5] relational database with the open source platform pgAdmin[6] and PostGIS[7] extension. The analyses were performed by using the free and open source Geographic Information System (QGIS[8]). First of all, the dataset was cleaned to remove duplicate records, erroneous positions, and the signals registered within 1 km to the harbours, in order to disregard the moored vessels. Hence, the signals of each vessel were interpolated considering all the points recorded from the departure to the return to the port. After an accurate analysis of the vessels speed frequencies distribution (**Supplementary Figure 1.1**) the vessels speed range of each fishing segment was defined (**Supplementary Table S1.1**) and used for the identification of the fishing activities (fishing/no fishing). Subsequently, to identify each single fishing track, the portions of the segments where the speed fell within the fishing speed range was sub-selected. Each fishing track was intersected in a grid of 1 km^2 and the fishing effort of each cell was estimated, according to

Equation 1.1

$$\boldsymbol{FE}_{\boldsymbol{V}}(\boldsymbol{c}) = \frac{\boldsymbol{SWA}_{\boldsymbol{V}}\,(\boldsymbol{c})}{\boldsymbol{area}\,(\boldsymbol{c})}$$

with

Equation 1.2

$$\boldsymbol{SWA}_{\boldsymbol{V}}\,(\boldsymbol{c}) = \sum_{\boldsymbol{vessel} \in \boldsymbol{V}} \boldsymbol{len}\,(\boldsymbol{fishing}(\boldsymbol{vessel}) \cap \boldsymbol{c}) * \boldsymbol{net\ opening}\,(\boldsymbol{vessel})$$

where V is the set of vessels, c is the cell, *area* is the area of the cell (1 km^2), *len (fishing*

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[5] http://www.postgresql.org

[6] https://www.pgadmin.org/

[7] http://postgis.net

[8] https://www.qgis.org/en/site/

(vessel)) is the distance (km) covered during the trawling activities by each vessel, *net opening* is the width of the net (km; **Supplementary Table S1.1**). Following a literature research (D’Onghia et al., 1997; Giovanardi et al., 2011 in the Book “The state of Italian marine fisheries and aquaculture”; Lucchetti and Sala, 2012), interview with local fishermen, and considering that several factor influence the horizontal net opening (depth, towing speed, gear, etc) we used a fixed net opening value of 20 m for all the gears considered in the analyses, independently from the length of the vessels.

Analyses were carried out on both annual and seasonal basis for each fishing gears (LOTB, SOTB, RAP and PTM) and all of them cumulated, clustering the fishing effort into classes, where a value of 100% indicates that in one year each cell was entirely exploited.

The method was also applied to explore two different case studies: the displacement of the fishing effort caused by the fishery ban in the Pomo Pit area during the period comprised between July 2015 and July 2016, and possible effects related to the extension of the trawling activities ban to the 6 nm from the coast on different fishing segments. In the first case study, the fishing effort recorded in the two periods (ban/no-ban) was assessed both inside (2753 km^2) and outside (considering a buffer of 3167 km^2 surrounding the protected area) the Pomo Pit area. Since the analysis of the global fishing effort disaggregated per fishing gears highlighted that this area was exploited almost exclusively by LOTB, the analysis was not carried out at gears level. Otherwise, in order to highlight the most impacted fishing gears, in the second case study the fishing effort recorded in the area comprised between 3 and 6 nm was evaluated at gears level.

1.3 Results

1.3.1 Global pattern

The high-resolution distributions of the fishing effort for all the trawlers (LOA over 15 m) operating in the GSA17 for 2015 and 2016, are reported in **Figure 1.2**. The spatial pattern and the total swept area (108753 km^2 and 114439 km^2 in 2015 and 2016, respectively) resulted to be quite stable across the two years, with the exception of the Pomo Pit, where the fishing effort resulted lower in 2016. Regardless from the year, clear differences were detected in comparison between the East and West coast, with the latter hosting areas with the highest fishing effort (exploitation rate > 500%, meaning that each cell has been entirely exploited more than 5 times per year). The areas showing the lowest fishing effort were located along the median axis of the basin in correspondence to the so-called “Sole sanctuary”, as well as in the East basin (**Figure 1.1; Figure 1.2**).

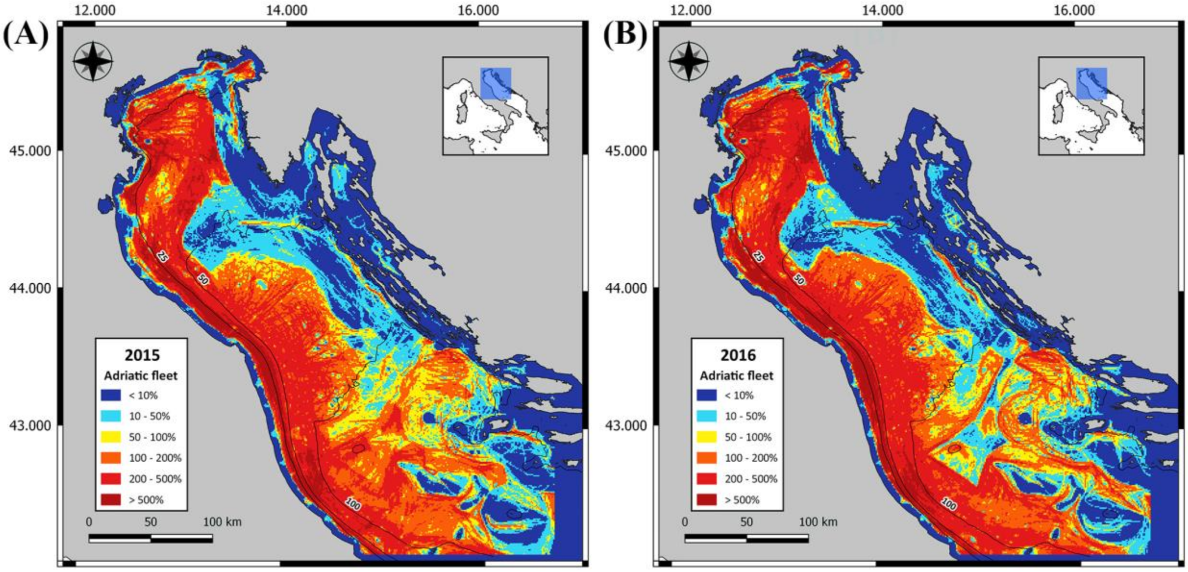

Figure 1.2. Fishing effort distribution for trawling fleet in the Northern and Central Adriatic Sea (GSA 17), in 2015 **(A)** and 2016 **(B)**.

According to data assessed on the annual basis, the 45% of the GSA17 resulted to be intensively exploited, being each cell completely swept from 1 to over 5 times per year (**Table 1.2**), while only the 13% of the GSA resulted totally not explored by fishing activity. Specifically, the fishing effort resulted medium-high (100 - 200%) in 18% (2015) and 17% (2016) of the GSA17. High values of fishing effort (200 - 500%) were recorded in 16192 km^2 (22% of the area, 2015) and 17345 km^2 (23% of the area, 2016), resulting the most represented class. Finally, in 5% and 6% of the area the fishing effort was very high (> 500%). Concerning the Northern and the Central basin, about the 40% of the highest fishing effort (over 100%) was distributed in the Northern basin and about the 60% in the Central one. Moreover, the major contribution to the total fishing effort came from the Italian trawl fleet, representing the 88% (2015) and 89% (2016) of the total studied fleet.

Table 1.2. Fished area (FA, km^2 and %) and fishing effort (FE, mean + SD), per class of FE in 2015 and 2016.

Adriatic Fleet	**2015**			**2016**		
FE class	**FA**		**FE**	**FA**		**FE**
%	*km^2*	*%*	*mean ± SD*	*km^2*	*%*	*mean ± SD*
< 10	10558	14	0.037 ± 0.02	11346	15	0.036 ± 0.03
10 - 50	12879	17	0.263 ± 0.11	12036	16	0.250 ± 0.11
50 -100	8357	11	0.740 ± 0.14	7229	10	0.736 ± 0.15
100 -200	13572	18	1.475 ± 0.29	12584	17	1.485 ± 0.28
200 - 500	16192	22	3.028 ± 0.79	17345	23	3.107 ± 0.81
> 500	3898	5	7.624 ± 3.04	4529	6	7.281 ± 2.54
	65456	**87**		**65069**	**87**	

The relationship between fishing effort and distance from the nearest harbour was also assessed (**Figure 1.3**). Regardless from the year, even if the maximum recorded distance was of 108 km, the highest fishing effort levels were recorded between 6 and 20 km, with a pick at 15 km and a second small pick between 40 and 60 km (**Figure 1.3**).

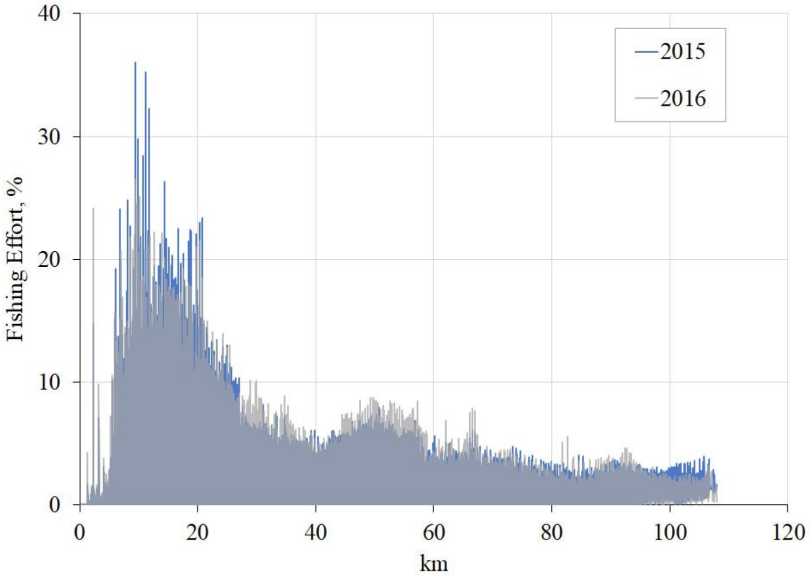

Figure 1.3. Fishing effort and the distance from the nearest harbour relationships, recorded in 2015 and 2016.

1.3.2 *Fishing gears*

Regardless from the years, the contribution of each fishing gear to the total fishing effort, expressed as percentage, highlighted that LOTB fleet played a key role in total amount of fishing effort, reaching more than 50% of incidence, and followed by RAP (~ 20%), SOTB (~ 17%) and PTM (~ 8%) (**Supplementary Figure S1.2**). However, standardizing the total fishing effort of each fishing gear for the number of vessels, RAP resulted the most important segment contributing for 44% to the total fishing effort, whereas the contribution of the others fishing segments was about 26% for LOTB, 17% for SOTB and 13% for PTM. (**Supplementary Figure S1.3**).

The annual high-resolution maps of the 4 fishing gears (LOTB, SOTB, RAP and PTM), showing the exploitation of different fishing grounds, are reported in **Figure 1.4**. Due to the absence of significant differences between the two years, only the 2015 maps are reported in the following figures.

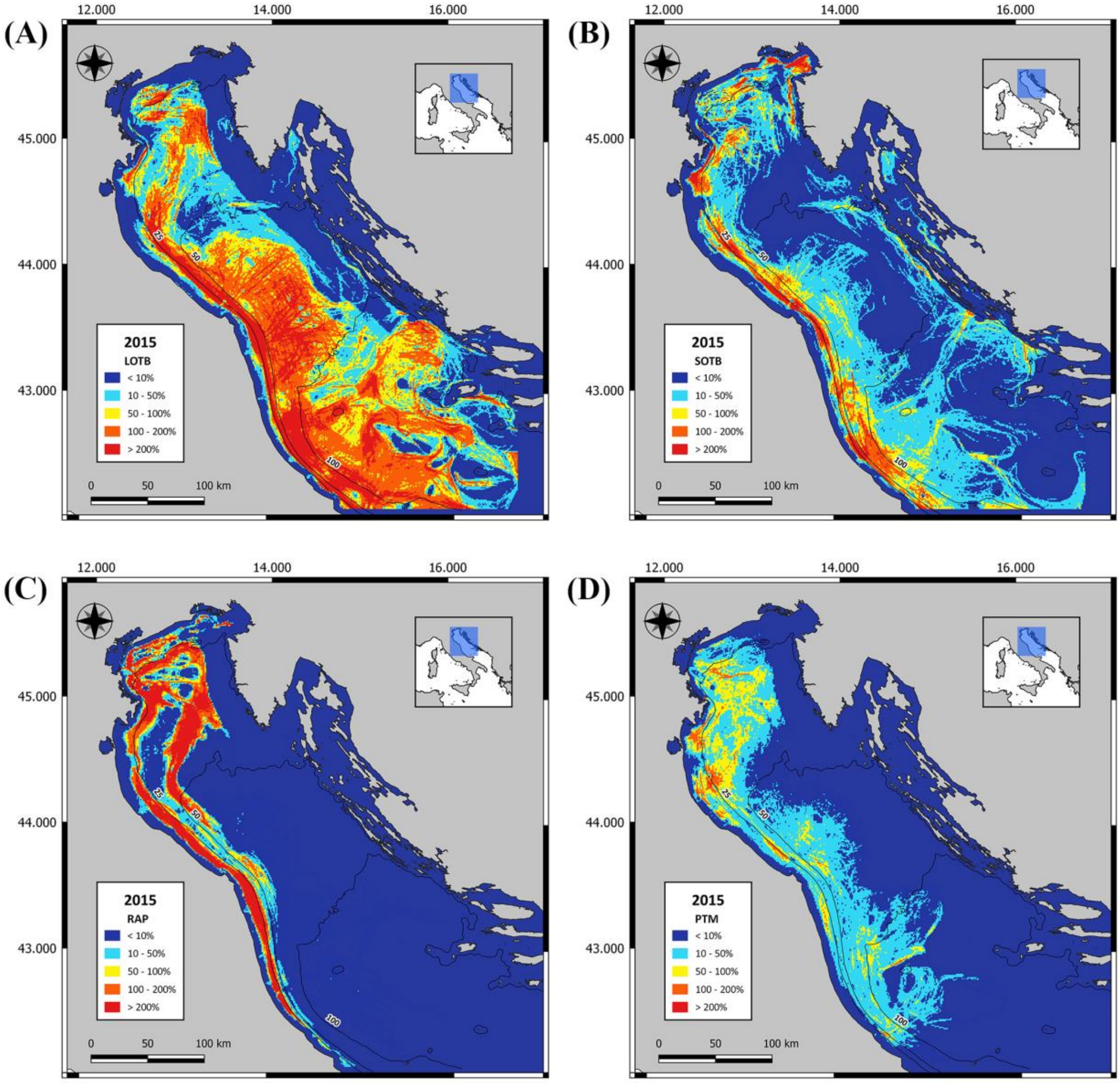

Figure 1.4. Fishing effort distribution for each fishing gears: **(A)** LOTB, **(B)** SOTB, **(C)** RAP and **(D)** PTM in the Northern and Central Adriatic Sea (GSA 17), in 2015.

In general, the LOTB fleet showed the widest exploited area, covering almost the entire Italian basin, excluding the Gulf of Trieste, and part of the southernmost Croatia. Even if the average fishing effort resulted highest in the bathymetry 15-35m (137%), it was very high also in the other strata (**Figure 1.5**). Moreover, the LOTBs activities were mainly concentrated in the Central basin, reaching about the 70% of incidence. The fishing effort of the SOTB fleet was mainly concentrated in the coastal area, inside the bathymetry of 15-35 m (**Figure 1.5**) and, differently from the other fleets, its activities interested also the Gulf of Trieste and part of the Istrian peninsula. Moreover, the fishing effort resulted equally distributed between the Northern and Central basin. The fishing grounds of the RAP fleet were totally localized in the Italian sub-basin, along the entire coastal area, excluding the southernmost part of the Central basin and the Gulf of Trieste. Moreover, the fishing effort resulted very high also in the offshore area of the Northern basin, which was the most exploited basin (~ 80%). Appreciable value of fishing effort was recorded under 100 m of deep, reaching the maximum fishing effort in the stratum 15-35 m (**Figure 1.5**). Compared to the other fishing gears, the PTM fleet produced the lowest fishing effort (**Supplementary Figure S1.2**) and the fishing grounds seem to be less defined and spread (**Figure 1.4**), with the fishing activities mainly concentrated in the Northern basin (~ 67%).

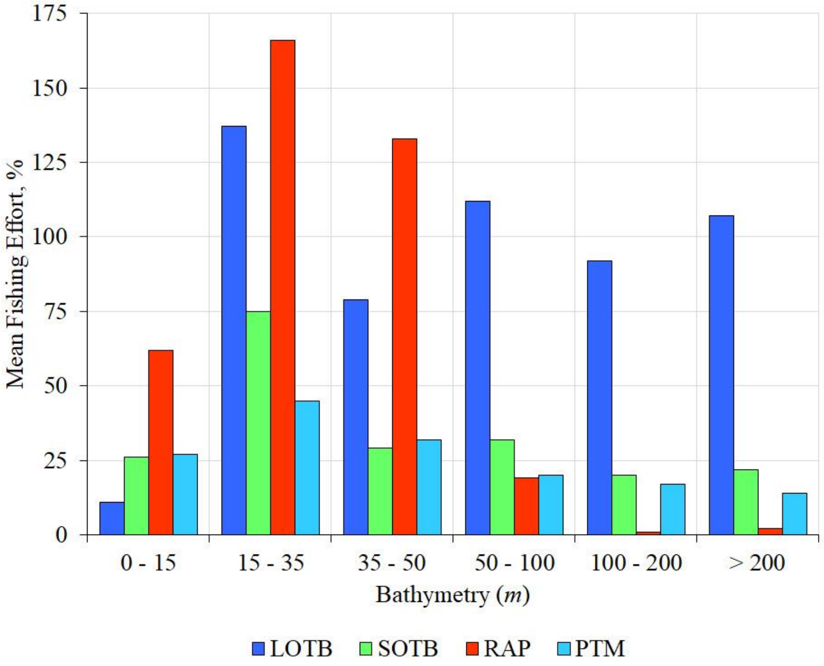

Figure 1.5. Average fishing effort per bathymetric strata (m) and fishing gear.

1.3.3 Seasonal fishing effort

The seasonal fishing effort, disaggregated per fishing gear and expressed as percentage of incidence in the season, highlighted a quite stable pattern of distribution across the fishing segments, being the autumn the most active season for all the gears (**Table 1.3**; **Table 1.4**; **Table 1.5**; **Table 1.6; Supplementary Figure S1.4**).

The seasonal high-resolution maps of fishing effort of the LOTB showed clear different patterns in the four seasons, with the fishing activities more concentrated both in the coastal and offshore area in winter, mainly offshore in spring, patchily distributed in summer and mostly coastal in autumn (**Figure 1.6**; **Table 1.3**).

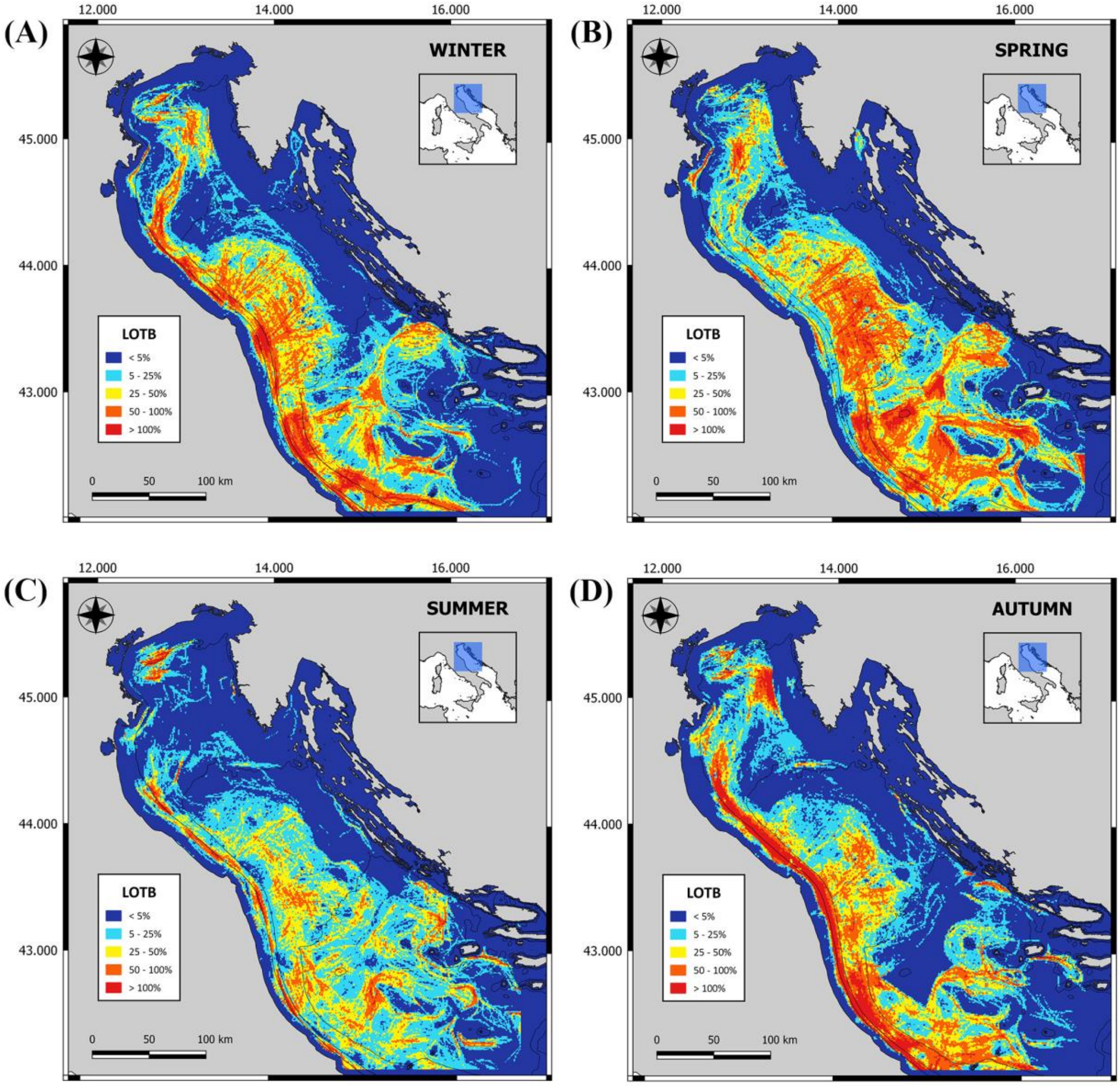

Figure 1.6. Seasonal fishing effort of LOTB, in 2015. **(A)** winter, **(B)** spring, **(C)** summer and **(D)** autumn.

Table 1.3. LOTB fished area (Area, km^2) and fishing effort (FE, mean ± standard deviation, SD) per FE class (percentage, %) and season: winter, spring, summer and autumn (2015).

LOTB	**Winter (24%)**		**Spring (29%)**		**Summer (17%)**		**Autumn (30%)**	
FE class *%*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*
< 5	12156	0.023 ± 0.01	9882	0.022 ± 0.01	11728	0.022 ± 0.01	11452	0.022 ± 0.01
5 - 25	16047	0.134 ± 0.06	16339	0.134 ± 0.06	21078	0.139 ± 0.06	15475	0.133 ± 0.06
25 -50	10469	0.363 ± 0.07	12760	0.365 ± 0.07	11518	0.349 ± 0.07	9141	0.364 ± 0.07
50 -100	7787	0.685 ± 0.13	10434	0.691 ± 0.13	3617	0.652 ± 0.13	6628	0.681 ± 0.13
> 100	1945	1.347 ± 0.37	2118	1.258 ± 1.68	540	1.346 ± 0.39	3315	2.259 ± 1.68

The seasonal high-resolution maps of SOTB fishing effort showed quite similar seasonal patterns, with the highest fishing pressure concentrated in the coastal area. Nevertheless, while the fishing grounds resulted more homogeneous in autumn, they were patchily distributed in the other seasons (**Figure 1.7; Table 1.4**).

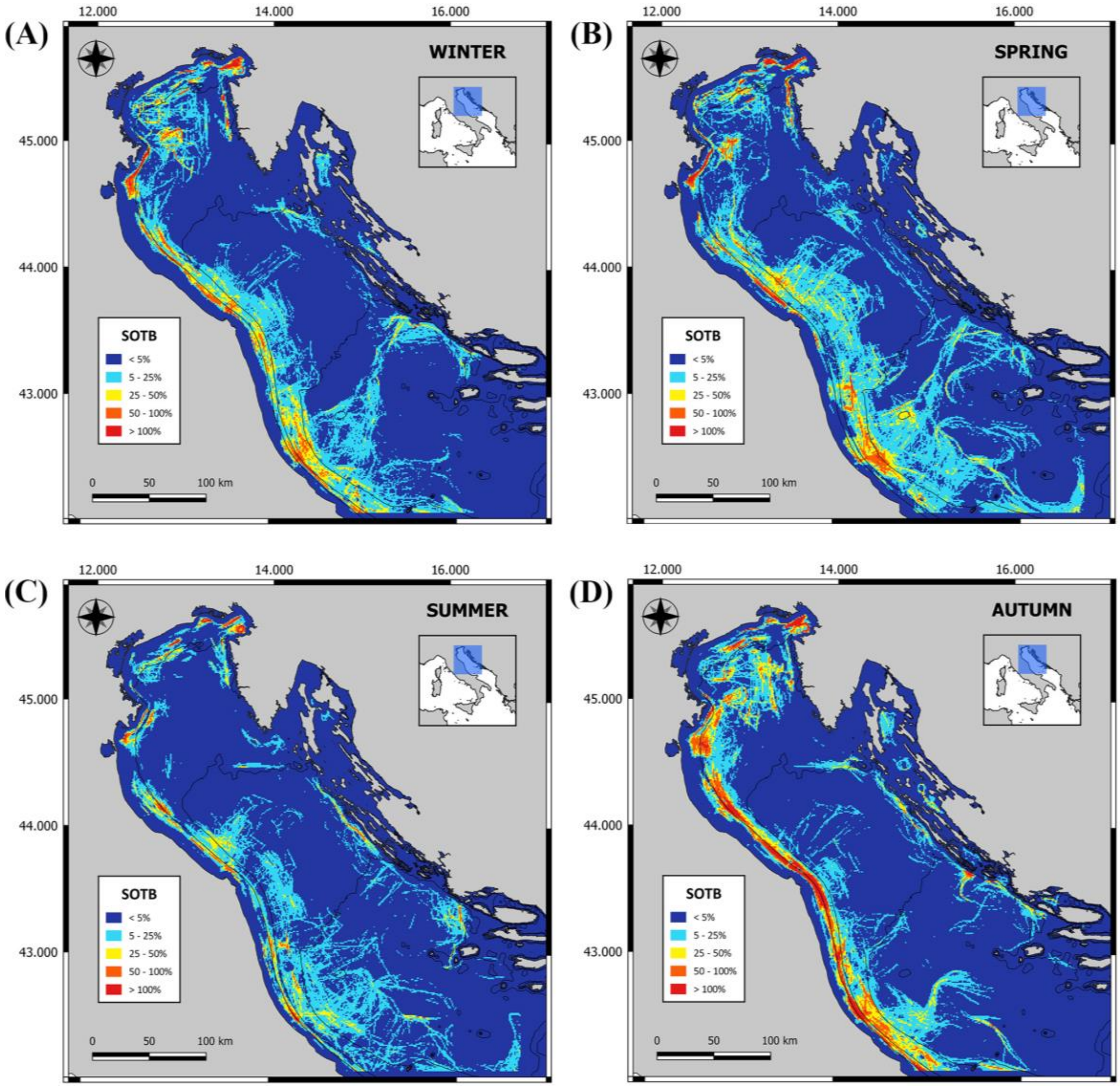

Figure 1.7. Seasonal fishing effort of SOTB, in 2015. **(A)** winter, **(B)** spring, **(C)** summer and **(D)** autumn.

Table 1.4. SOTB fished area (Area, km^2) and fishing effort (FE, mean ± standard deviation, SD) per FE class (percentage, %) and season: winter, spring, summer and autumn (2015).

SOTB	**Winter (23%)**		**Spring (28%)**		**Summer (17%)**		**Autumn (32%)**	
FE class	**Area**	**FE**	**Area**	**FE**	**Area**	**FE**	**Area**	**FE**
%	*km^2*	*mean ± SD*	*km^2*	*mean ± SD*	*km^2*	*mean ± SD*	*km^2*	*mean ± SD*
< 5	15536	0.023 ± 0.01	17697	0.023 ± 0.01	18559	0.022 ± 0.01	15203	0.021 ± 0.01
5 - 25	14125	0.117 ± 0.06	19152	0.120 ± 0.05	13448	0.112 ± 0.05	11699	0.120 ± 0.05
25 -50	3299	0.345 ± 0.07	3644	0.337 ± 0.07	1917	0.335 ± 0.06	3493	0.353 ± 0.07
50 -100	1112	0.665 ± 0.13	1058	0.668 ± 0.13	527	0.669 ± 0.13	1962	0.686 ± 0.13
> 100	262	1.460 ± 0.37	329	1.799 ± 1.20	121	1.298 ± 0.31	958	2.259 ± 0.71

The fishing effort of RAP, displayed in the seasonal high-resolution maps, showed very similar fishing grounds (**Figure 1.8; Table 1.5**). In particular, in winter and autumn, the fishing activities were concentrated both in the coastal and offshore area, while in spring lower value of fishing effort have been recorded in the offshore area. In this season, an increase of the fishing effort was evident in the area close to the Po River Delta. Differently, in summer the fishing effort resulted very low in all the investigated area.

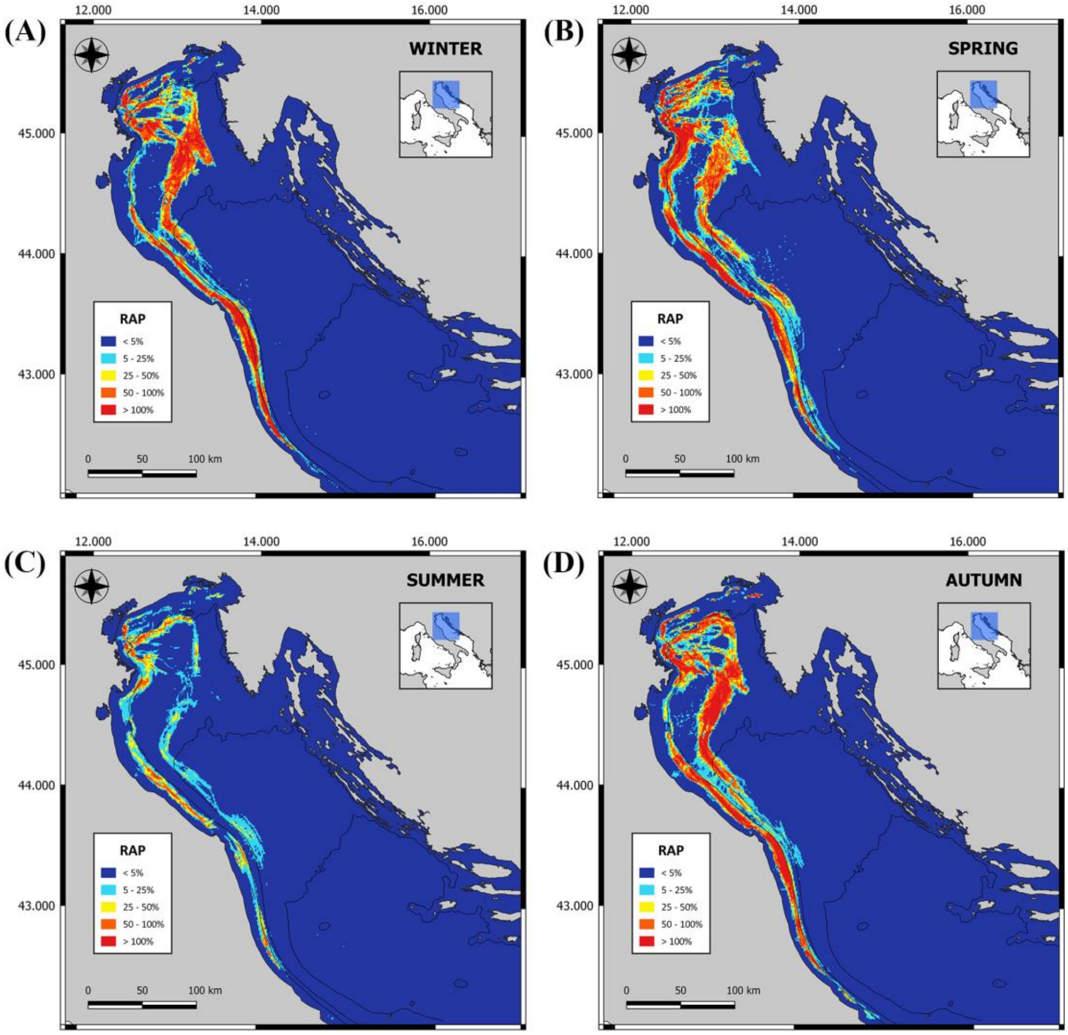

Figure 1.8. Seasonal fishing effort of RAP, in 2015. **A)** winter, **(B)** spring, **(C)** summer and **(D)** autumn.

Table 1.5. RAP fished area (Area, km^2) and fishing effort (FE, mean ± standard deviation, SD) per FE class (percentage, %) and season: winter, spring, summer and autumn (2015).

RAP	**Winter (26%)**		**Spring (29%)**		**Summer (15%)**		**Autumn (30%)**	
FE class *%*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*
< 5	5758	0.016 ± 0.01	7058	0.017 ± 0.01	10115	0.016 ± 0.01	4761	0.018 ± 0.01
5 - 25	2888	0.127 ± 0.06	4032	0.127 ± 0.06	3594	0.123 ± 0.06	3324	0.129 ± 0.06
25 -50	1635	0.367 ± 0.07	2224	0.363 ± 0.07	1741	0.361 ± 0.07	1717	0.366 ± 0.07
50 -100	2107	0.739 ± 0.14	2499	0.713 ± 0.13	1295	0.709 ± 0.14	2054	0.721 ± 0.14
> 100	1989	1.609 ± 0.83	1982	1.65 ± 0.79	722	1.564 ± 0.67	2425	1.659 ± 0.65

The seasonal high-resolution maps of fishing effort of PTM highlighted that the fishing activities, generally very low and patchily distributed in all the seasons, were quite higher in autumn and spring, in the coastal area (**Figure 1.9; Table 1.6**).

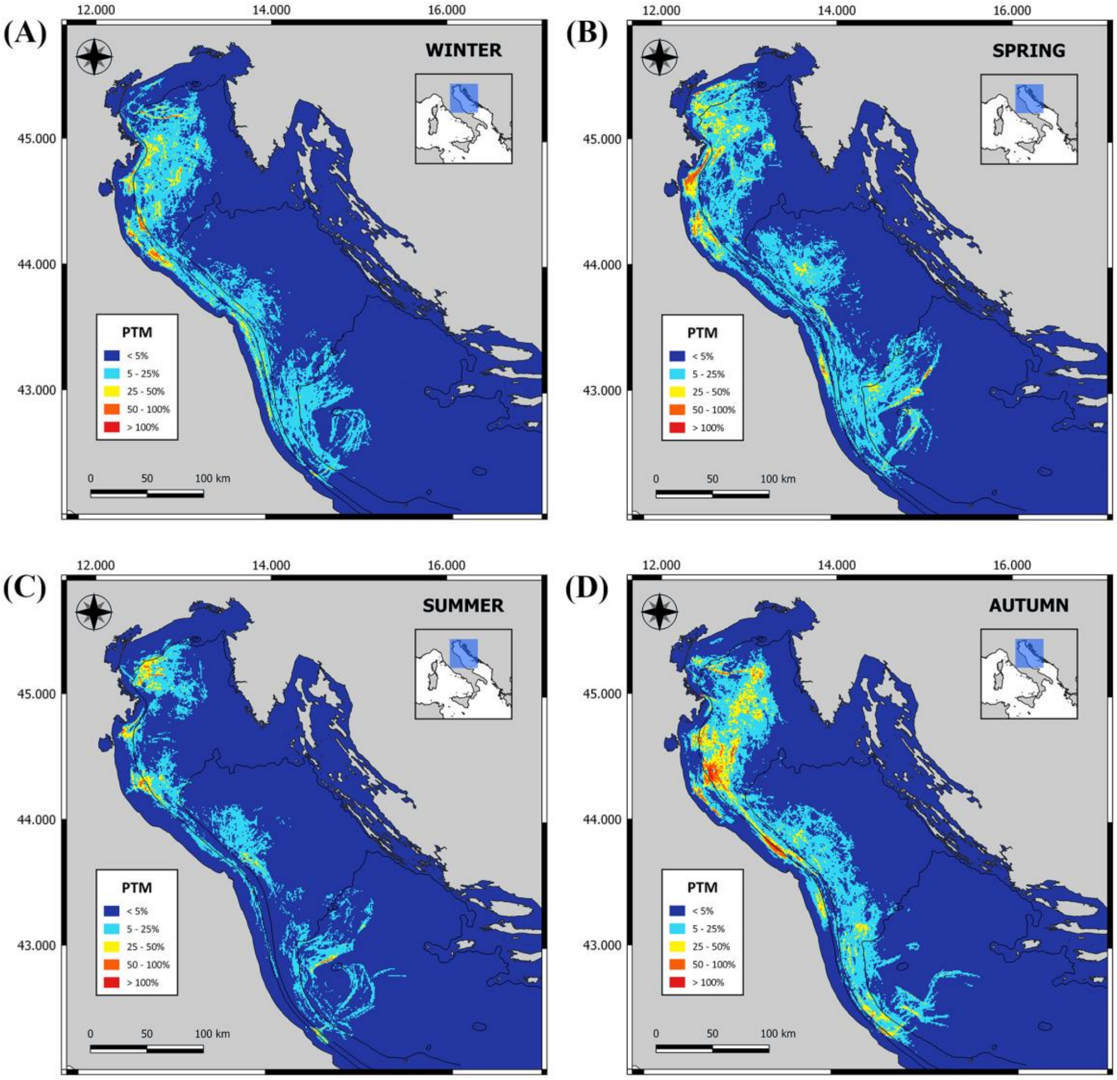

Figure 1.9. Seasonal fishing effort of PTM, in 2015. (**A)** winter, **(B)** spring, **(C)** summer and **(D)** autumn.

Table 1.6. PTM fished area (Area, km^2) and fishing effort (FE, mean ± standard deviation, SD) per FE class (percentage, %) and season: winter, spring, summer and autumn (2015).

PTM	**Winter (26%)**		**Spring (29%)**		**Summer (15%)**		**Autumn (30%)**	
FE class *%*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*	**Area** *km^2*	**FE** *mean ± SD*
< 5	8755	0.024 ± 0.01	10235	0.025 ± 0.01	10204	0.023 ± 0.01	7304	0.024 ± 0.01
5 - 25	11929	0.116 ± 0.05	13707	0.114 ± 0.05	7290	0.103 ± 0.05	11754	0.124 ± 0.05
25 -50	1142	0.323 ± 0.06	1638	0.328 ± 0.06	716	0.337 ± 0.07	2626	0.339 ± 0.07
50 -100	127	0.611 ± 0.09	214	0.654 ± 0.12	89	0.593 ± 0.09	487	0.640 ± 0.12
> 100	2	2.58 ± 0.95	15	1.25 ± 0.38	1	1.986 ± 0.00	65	1.247 ± 0.63

1.3.4 Case studies

1.3.4.1 Pomo Pit

The Pomo Pit area, covering 2753 km^2, was mainly exploited by LOTB. A total of 5167 km^2 of swept area (exploiting rate of 188%) was recorded inside the Pomo Pit during the no-ban period (from 1st January 2015 to 26th July 2015 and from 27th July 2016 to 31st December 2016). If from one side, the ban (from 27th July 2015 to 26th July 2016) produced a strongly reduction of the fishing effort in the protected area, from the other side, this fishing effort was partially redistributed outside in the surrounding area (3167 km^2), producing an increase of 42% (1807 km^2) of the fishing effort recorded in this area (no-ban period: 4260 km^2; ban period: 6067 km^2).

1.3.4.2 6 nm ban

In relation to the possible implementation of the trawling activities ban in the 3-6 nm from the coast area, the analysis highlighted that the total fishing effort recorded in this area represented 17% of the total fishing effort recorded for the Italian area, with an exploitation rate of about 400%, meaning that each cell was entirely exploited more than 4 times per year. In the event that the ban would be implemented, the most impacted fishing gears would be RAP and SOTB, which concentrated respectively the 35% and 20% of their activities in this area.

1.4 Discussions

The analysis of the annual high-resolution distribution of trawl fishing effort, allowed to identify accurately the mainly exploited areas of the GSA17 and the most impacting fishing gears, confirmed a high trawl fishing pressure in the Northern and Central Adriatic Sea (AdriaMed, 2004; Barausse et al., 2009; Pranovi et al., 2015; Fortibuoni et al., 2017), for which many stocks have been recognized as overexploited (Adriamed, 2004; Colloca et al., 2013; Fortibuoni et al., 2017). In particular, about 45% of the area resulted entirely exploited from 1 to over 5 times per year. It is worth noting that the real degree of exploitation of the GSA17 was higher than the one here estimated, being the trawlers with a LOA < 15 m (about 500 trawlers) not considered in this work. Regarding the three countries involved, the Italian side resulted the most exploited, while low fishing effort was recorded in Croatia, excluding the southernmost part, and in Slovenia. The notably difference among these countries was due to the size of the Italian trawl fleet, which is the biggest. Throughout the two years, a similar spatial distribution of the fishing grounds was detected, highlighting temporal and spatial aggregation patterns and fleet's dynamics. In particular, non-random behaviours of the Adriatic trawl fleet, supposedly influenced by handed down patterns of fishing performance, regulatory limitations and bathymetric features, were observed. Generally, the highest values of fishing effort were recorded within the bathymetric range of 15-35 m, with a decreasing pattern moving off from the coast. All this has been confirmed also by the relation between the location of the fishing grounds and the nearest departure harbour. Indeed, the maximum spatial density of high values of fishing effort was recorded around 15 km from the nearest port. However, LOTB and RAP showed also the presence of fishing grounds located in the offshore area, explaining the high concentration of fishing effort recorded between 40 and 60 km from the nearest port. Low fishing effort values (exploitation rate <50%) were recorded in the so-called "Sole Sanctuary", a persistent sole spawning area located in the middle of the Northern basin between Rimini and the Istrian peninsula (Scarcella et al., 2014). As reported by previous studies (Grati et al., 2013; Scarcella et al., 2014; Bastardie et al., 2017; Santelli et al., 2017), the reasons for this would be, on one side the high concentration of bryozoans (*e.g.*, *Amathia semiconvoluta*; Salvalaggio et al., 2014), which makes the seabed untrawlable for the risk to obstruct the nets, and on the other the high presence of holothurians (*e.g.*, *Holothuria forskali* and *Parastichopus regalis*), characterized by the capacity to eviscerate their internal organs under stress conditions, which makes the fishery resources less saleable (Bastardie et al., 2017).

The annual high-resolution distribution of the fishing effort per fishing gears, steady for the two years, showed clear differences among the 4 fleets (SOTB, LOTB, RAP and PTM), highlighted also by the fishing effort distribution per bathymetric stratum. The main contribution to the total fishing effort was due to the LOTB (> 50%), which showed the widest exploited area (~ 48000 km^2), as well as the major number of fishing vessels. On the other side, the fishing effort produced by RAP fleet, accounting for about 20% of the total one, was concentrated in smaller fishing grounds (~ 16000 km^2), so causing a heavy exploitation of the coastal zone. Moreover, the normalization of the fishing effort per number of vessels, highlighted very high value of fishing effort caused by RAP. The presence of well-defined fishing grounds for this fishing gear depended on its target species which have specific distributions. Indeed, RAP are used by the Italian fleet to catch mainly flatfishes, in the inshore muddy bottoms, and pectinids (*Pecten jacobaeus* and *Aequipecten opercularis*) in the offshore sandy bottoms (Pranovi et al., 2000). A modest fishing effort, mainly located along the coastal areas, was recorded for the SOTB fleet. Differently from the other fishing gears, this fishing activities were recorded also in the Gulf of Trieste, as well as in the northern part of the Istrian peninsula. PTM, which is the principal fishing gear used by the Italian fleet to catch small pelagic species (*e.g.*, *Engraulis encrasicolus* and *Sardina pilchardus*), showed a peculiar fishing behaviour. Indeed, the distribution of this activity is directly dependent on the presence of school fish, which are localized using echosounder and sonar (FAO, 2003). Therefore the fishing grounds were not well defined and the fishing effort resulted lower than the others fishing gears. Moreover, since the main gear used to catch small pelagic species in Croatia and Slovenia is the Purse Seine ("Status and conservation of fisheries in the Adriatic"; UNEP-MAP-RAC/SPA, 2014), the fishing effort of the PTM was not recorded in these countries.

The seasonal distribution of the fishing effort resulted quite similar for all the fishing segments. In particular, regardless from the fishing gears, the fishing activities were mainly concentrated in autumn and spring, reaching about the 31% and 29% of the annual incidence, respectively. The high fishing effort recorded in autumn could be a consequence of the summer biological recovery period, during which the trawling activities were forbidden in Italy. Otherwise, the spatial distribution of the fishing effort, following different patterns related to fishing segment and season, could be influenced by the weathering conditions and the distribution of the main target species. Even if the high spatial and temporal resolution of AIS data, used for the evaluation of the fishing activities, can compensate the lack of information relative to the species data (Natale et al., 2015), other studies taking into account also the fishing catches and the benthic assemblages should be recommended in order to better explain these fishing strategies.

The exploration of the two case studies have shown the possibility to implement this methodology within the fishing management context, such as for the evaluation of the effects due to past and future management strategies. According to the spatial distribution of the fishing effort, it was possible to assess the side effects due to the temporary closure of the Pomo Pit, with a significant increase of the fishing effort in the area around the closed zone. However, it is worth noting that this increase accounted for just a portion of the effort missed with the closure (less than 50%), suggesting a complete change of the fishing strategies adopted by a consistent portion of the trawling fleet operating in that area. About the case study concerned a hypothetical ban for trawling activities within 6-nm from the Italian coast, the analyses have highlighted an intensive exploitation of this area, especially by RAP and SOTB fleets. In fact, some target species of RAP are mainly located in the coastal area (Pranovi et al., 2015), and due to the small dimensions of the vessels the SOTB avoids operating in areas too far from the coast. Therefore, these two fleet segments would be the most negatively affected by the ban. All this confirmed that the closure of the 6nm-area would reduce the fishing grounds for trawlers and, as highlighted for the Pomo Pit area, a possible spill-over effect should be considered in order to avoid an increase of the pre-existent fishing effort.

Overall, these results could be useful within the contest of the implementation of new fisheries management strategies in the GSA17 and also at fishing gear level.

1.5 Conclusions

In the context of the European environmental directives and strategies, the present study confirms AIS as a useful tool to analyse human impacts on the seas biodiversity and help decision makers to implement mitigation strategies. We are aware that AIS data have some limitations for the estimation of fishing effort, related with spatial coverage and the size of the vessel equipped with this system (> 15 meters). However, the benefits provided from this source of data, in terms of fish stock assessment, detection of illegal fishing activity and identification of fishing grounds, has been demonstrated in different papers (*e.g.*, Ferrà et al., 2018; Shepperson et al., 2018).

As highlighted by our results, mapping fishing effort at high spatial and temporal resolution represents an important step to analyse the impact of fishing activities on the ecosystem, as well as to monitoring these activities and the efficiency of the management strategies, in line with the Marine Strategy Framework Directive (MSFD; 2008/56/EC), the more recent Maritime Spatial Planning (MSP; 2014/89/EU), and the Sustainable Development Goal (SDG[9]) 14 “Life Below Water” (UN, 2015).

Even if other authors had employed AIS data to evaluate and map the fishing activities on European (Natale et al., 2015; Vespe et al., 2016) and Mediterranean scale (Ferrà et al., 2018),

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[9] https://sustainabledevelopment.un.org/sdgs

in this paper we focused our analyses at the GSA level, obtaining a more accurate assessment of the trawling activities, catching spatial and temporal patterns. Moreover, the methodology here applied, considering the real trajectory of each vessel together with the swept area, is a relevant example of fishing effort estimation, in line with the ICES recommendation (2015). However, since this method suffer of uncertainty due to the discrimination of the fishing phase by using only the fishing speed, and to the utilization of a fixed value (20 m) for the net opening used to estimate the swept area, sensitivity analysis would be taken into consideration for future works in order to estimate the uncertainty.

Another novelty aspect of the present paper was the assessment of the fishing effort for different fishing gears (*i.e.*, LOTB, SOTB, RAP and PTM), a level of detail which could help to detect different efficiency level of fisheries and could be a baseline to implement specific management action for these activities.

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Appendix I

Supplementary Figures

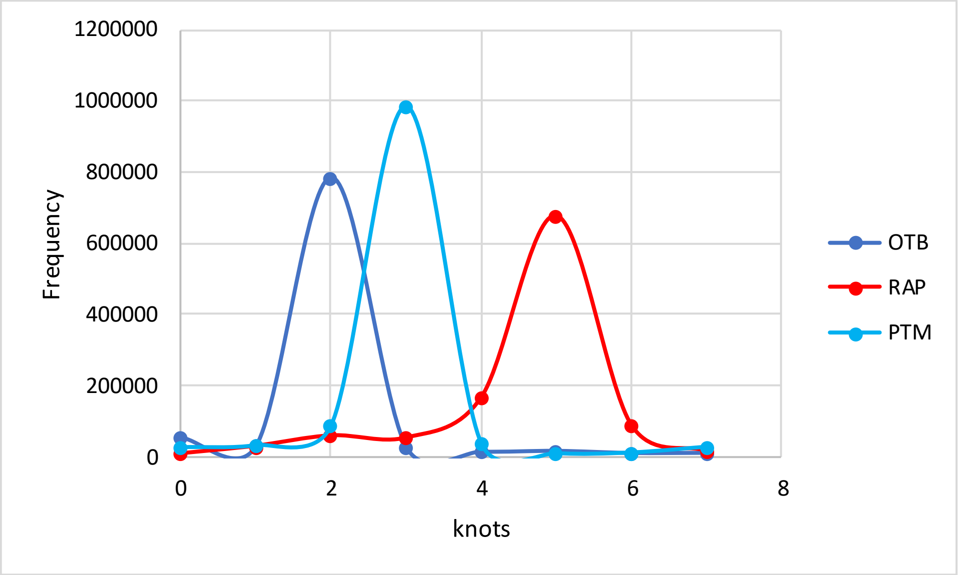

Figure S1.1. Speed histogram of the frequency distribution of the fishing segments (OTB, RAP and PTM)

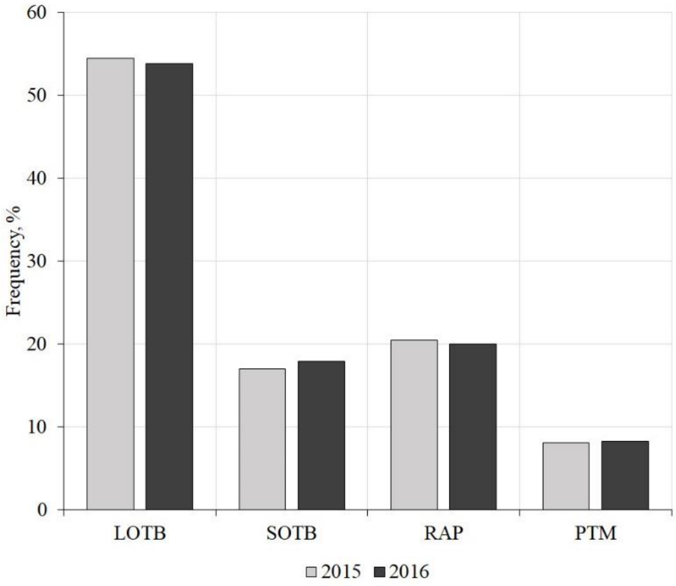

Figure S1.2. Contribution (expressed as percentage, %) of each fishing gears to the total FE in 2015 and 2016.

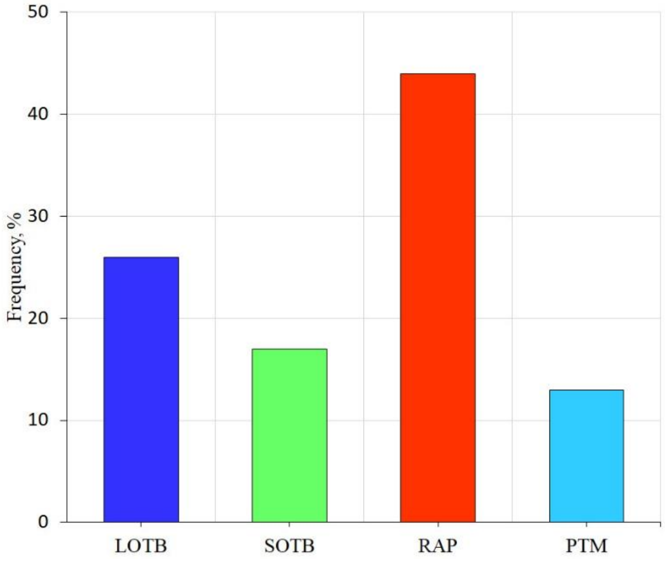

Figure S1.3. Contribution (expressed as percentage, %) of each fishing gear to the total FE, normalized for the number of vessels.

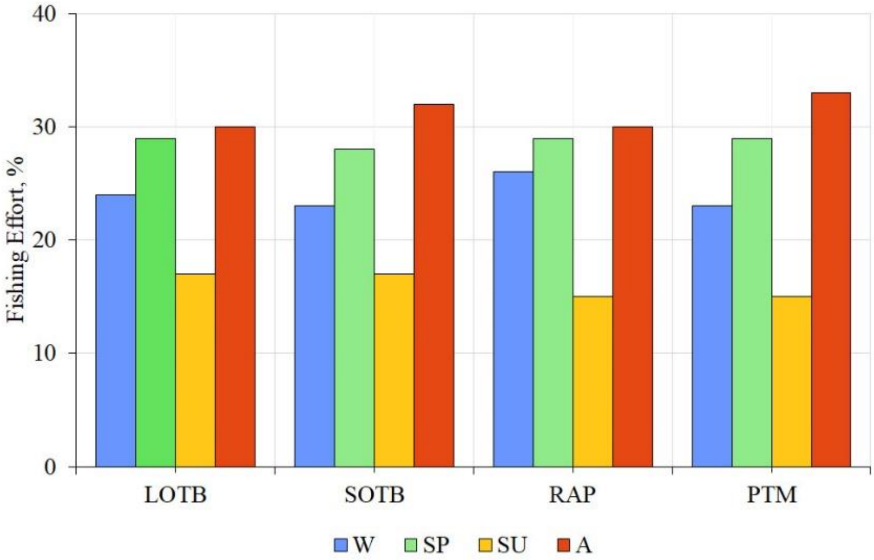

Figure S1.4. Seasonal fishing effort (expressed as percentage, %) of each fishing gear (LOTB, SOTB, RAP, PTM) expressed as percentage (%) of incidence; W=winter, SP= spring, SU=summer and A=autumn.

Supplementary Tables

Table S1.1. Speed ranges (knots) for the gears analysed (LOTB, SOTB, RAP and PTM); speed data selected according to Sala et al. (2011), Scarcella et al. (2014), Mangano et al. (2015) and Natale et al. (2015).

Fishing gear	**Speed range** *(knots)*
LOTB	2 - 4
SOTB	2 - 4
RAP	4 - 7
PTM	2 - 5

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Chapter 2. An integrated productivity index of trawl fishing activities in the Northern Adriatic Sea (GSA17)

Abstract

This work assessed the fishing activities of the Northern Adriatic Sea (GSA17) by using three data variables: landing data, economic value and fishing effort. Catches assessment on a spatial basis, associated with the fishing effort, represents one of the main challenges within the context of the implementation of the real Ecosystem Based Fishery Management (EBFM). The spatial distribution of the landing data of the Chioggia Fish Market, associated with economic value and fishing effort, estimated by using high-frequency Automatic Identification System (AIS) data, was carried out for 2016. The fishing grounds were also assessed on basis of the combination of the three variables, allowing us to identify the different degree of efficiency of the areas, where the maximum efficiency corresponded to high level of landing and economic value and low values of fishing effort. Moreover, the distribution pattern of the most profitable species was pointed out and high-resolution maps of these main target species were carried out on seasonal basis, highlighting seasonal changes on their distribution.

The analyses of the fishing productivity revealed that most of the northern part of the area was highly exploited, with high landing and economic value, while the southern basin, more distant from the homeport, resulted low exploited, with low landing and economic value. Moreover, the analyses performed for the four fishing gears (SOTB, LOTB, RAP and PTM) highlighted PTM as the most efficient gear, in relation to the three variables. Despite its limitations, our approach could be very useful in support of the fishery management. Indeed, different management strategies were recently proposed, and these regimentations need to be monitored in time and space, as well as the resulting effects should be assessed under environmental, social and economic point of views, and it is in this context that our approach could be very useful.

2.1 Introduction

The fishing activities, both industrial and artisanal, represent one of the most widespread human activities in the marine environment, as well as one of the major causes of disturbance (*e.g.*, O'Neill and Ivanović, 2016). These activities have direct and indirect effects on the entire ecosystem (*e.g.*, changes of the habitats structures and of trophic web) causing loss on biodiversity and alteration of the ecosystem functionality (Jennings and Kaiser, 1998; Jackson et al., 2001; Johnson et al., 2015; Mangano et al., 2015, 2017; Marra et al., 2016). In the meantime, fishing activities have high socio-economic value, representing one of the main sources of income and food, especially for coastal countries (FAO, 2016). In the European Union the amount of fish landed in 2017 was 4.5 million tonnes, with an income of 7.3 billion euro, and providing jobs for about 178 thousand people (Agriculture, forestry and fishery statistics, 2018). For this reason, the achievement of a sustainable fishery, on environmental, economic and social basis, is fundamental in order to ensure the availability of the marine resources for the future generations. Under the requirement of the 2030 Agenda for Sustainable Development, which established 17 Sustainable Development Goals (SDGs), and in particular with SDG 14 "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", the management of fishing activities need to be constantly monitored and new policies should be constantly integrated and implemented. In this context, one of the most important instruments used to manage the fishing activities in Europe is the Common Fishery Policy (CFP; 2013/1380/EC), whose primary goal was to guarantee sustainable fisheries, as well as income and stable jobs. However, in Mediterranean Sea the application of the CFP to manage the fishing activities, which are multi-species and multi-gears, resulted very challenging due to the complexity of the ecological, economic, social and political differences within this basin (Carpi et al., 2017; Libralato et al., 2018). During the years the CFP was reformed establishing a series of actions, such as the implementation of multiannual plans, the adoption of conservation measures and the application of precautionary principles. Moreover, the new CFP increased the focus on regionalization, which contributes to the implementation process at local level and adapts governance structures to the specific needs of regional seas.

In the European Union, others important directives with direct implication in the fishery management are the Marine Strategy Framework Directive (MSFD; 2008/56/EC), aiming the achievement of a Good Environmental Status (GES) of the European marine waters by 2020, and the Maritime Spatial Planning Directive (MSP; 2014/89/EU), for the promotion of the sustainability of the economic activities in the sea. These directives stressed the importance to implement the utilization of an ecosystem-based approach to the fishery management, as well as an integrated approach at regional and sub-regional level (Burgt et al., 2017; Libralato et al., 2018). In this context, catches assessment on a spatial basis and associated with the fishing effort represent one of the main challenges within the implementation of the Ecosystem Based Fishery Management (EBFM).

The Northern Adriatic Sea represent a suitable case study to highlight the importance to focus the research at regional scale. Indeed, this sub-basin of the Mediterranean Sea, characterized by high level of productivity, mainly due to the presence of river outlets, is object of very high levels of fishing effort (Barausse et al., 2009; Pranovi et al., 2015; Fortibuoni et al., 2017) that have led to the overexploitation of the fishery resources (Colloca et al., 2013; 2017; Fortibuoni et al., 2017). In this context, the improvement of efficient fishery management strategies is fundamental in order to reach a sustainable fishery, on environmental, economic and social basis, ensuring a productive and healthy ecosystem. The current fishery management is based on different strategies, such as the permanent and seasonal closure of the trawling activities (*e.g.*, the permanent closure within 3 nm from the coast and the seasonal biological rest period), technical measures (*e.g.*, mesh size of the net) or, recently, the *ad hoc* regulations enforced in the Adriatic Sea (GSA 17 and 18) setting limits on the fishing of small pelagic fishes.

Previous works have already investigated the fishing effort in the Adriatic Sea (*e.g.*, Russo et al., 2019), as well as the species distribution, coming from scientific survey programs (such as the International bottom trawl survey in the Mediterranean Sea [MEDITS], the Solea Monitoring project [SoleMon], etc.) and landing time series using data of the Chioggia Fish Market (Fortibuoni et al., 2017). However, scientific surveys sites have limited coverage in space and time, since they are usually conducted once in a year, and therefore the evaluation of the species distribution and their changes results difficult at high spatial and temporal resolution (ISPRA, 2016). On the other hand, time series of landing data do not provide information about the spatial distribution of the catches associated with the fishing effort. In some countries the catches distribution was carried out by using logbook data, however in the Mediterranean countries these data are not very reliable, suffering of falsification, misreporting, and incompleteness (GFCM, 2009; STECF, 2013; Damalas, 2015). To overtake these issues, the use of geo-localization technology, such as Automatic Identification System (AIS), represents a valid tool. Indeed, the use of AIS data is becoming increasingly prevalent in the scientific community to monitoring and assess the fishing activities distribution and fishermen behaviour (Natale et al., 2015; Vespe et al, 2016). This system, designed for security purposes (*i.e.*, navigational aid to avoid vessel collisions) and currently mandatory for vessels with a length overall (LOA) over 15 m, allows to obtain the vessels positions with high temporal frequency (from 2 seconds to few minutes) and their trajectories. It is worth noting that even if these data present some limitations, mainly related to the data coverage and the vessels size (LOA > 15m), in the Adriatic Sea the AIS coverage is very high, ranging from 75 to 100% (Blue Hub tool of

Joint Research Centre[10]).

The aim of this work was to assess in a spatial base the trawl fishing activities in the Northern Adriatic Sea, by using an integrated index, combining landings, economic values and fishing effort. All these variables allowed to summarise in a single view both productivity and exploitation level of the different fishing grounds. Results could be useful within a context of implementation of new management strategy, such as spatio-temporal closures. One of the advantages to use daily landing and AIS data was the high temporal coverage of the results, allowing us to better evaluate their spatial and temporal distribution, also on seasonal basis. Moreover, the overlapping of these variables allowed to deeply evaluate the fishing activities on the basis of quali-quantitative distribution of catches and fishing effort. Moreover, the fishing area was also discriminated by considering the combination of the three variables (*i.e.*, landing, economic value and fishing effort), classified as 'high' and 'low', in order to highlight the different level of efficiency of the fishing grounds. In parallel, seasonal analyses of catches distribution of the main target species, recorded in the most profitable areas, were carried out.

2.2 Material and Methods

2.2.1 *Area of study and fleet*

The Northern Adriatic Sea, characterized by a wide continental shelf and eutrophic shallow waters, is located in the Geographical Sub Area [GSA] 17 (Central Mediterranean Sea). In this area, are located the so called 'Sole Sanctuary', a spawning area for soles, (Scarcella et al.,2014) and a Site of Community Importance (SCI), recently established to protect dolphins and sea turtles. The total studied area, limited to the Italian basin, covered a surface of 14600 km^2. The Italian Adriatic fishing fleet, with more than 3000 vessels belonging to small scale and industrial fishery, represent one of the widest fishing fleet in Italy, and the trawlers, having very high negative impact to the ecosystem, consist of about 800 units. In this study, only trawlers with a length overall (LOA) over 15 m and belonging to the Chioggia's fleet, which is one of the most important trawler fleet in the Italian waters, were taken into account in this study. In particular, 7 Small Bottom Otter Trawlers (SOTB; LOA from 15 to 18 m), 22 Large OTB (LOTB; LOA over 18 m), 36 *Rapido* Trawlers (RAP; a sort of beam trawler), and 16 Mid-Water Pair Trawlers (PTM, called also *Volante*), have been investigated. Since in the Northern Adriatic Sea, specifically in Chioggia (southern part of the lagoon of Venice), is located one of the most

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[10] https://bluehub.jrc.ec.europa.eu/mspPublic/ (last accessed September 2019)

important fishing harbours of this area, this study can be considered highly representative of the studied area.

2.2.2 Integrated index

The variables used in this work were landing data, economic values and fishing effort, obtained through the processing of AIS data. Fishing effort has been assessed in terms of swept area ratio, by using AIS data, provided by the Italian Coast Guard (ITC and Traffic Monitoring Department – Roma) and relative to 2016. Firstly, AIS data, stored in a data warehouse, were cleaned from erroneous position and duplicates. The tracks of each fishing vessels were obtained interpolating the signals issued by each trawler, from the leaving to the return in port, and using the vessels’ speed profile, peculiar for each fishing gear, to identify the vessels’ activities (fishing or no-fishing). Subsequently, the tracks of the fishing phase were selected and intersected in a grid (10x10 km) and the swept area was estimated multiplying the fishing tracks of each vessels for the net opening (20 m for all the gears) and summing them in all the cells. Finally, the swept area was divided for the area of each cell and the fishing effort was estimated. The latter was expressed as percentage of swept area, where 100% indicated that in a specific unit time (*i.e.*, year or season) the cell (100 km^2) was completely explored.

Daily landing data were collected by the Chioggia Fish Market, which is the most important fish markets of the Northern Adriatic Sea, hosting one of the main fleets of this basin. Landing and AIS data were merged together by using the Maritime Mobile Service Identity (MMSI) code, which is the identification number specific for each vessel and reported in the AIS data. Daily landing data (kg), were distributed to the fishing track of each vessel and summed in a pre-established cells grid (100 km^2).

In order to estimate the landing values, market price data of each landed species (euro/kg) specific to the Chioggia Fish Market, were obtained from the Italian Institute for Studies for the Agricultural and Food market (ISMEA[11]) database for 2016. Even if the ISMEA database reports the market price at different temporal resolution, considering that the standard error between monthly and annual data of the target species resulted low compare with the mean values (from 0.042 to 1.647), the annual average price (mean between minimum and maximum value) was took into consideration for the economic analyses. These values were associated to each species reported in the landing dataset and multiply for the quantity landed.

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[11] http://www.ismea.it/istituto-di-servizi-per-il-mercato-agricolo-alimentare

The two datasets, formed by landing, previously associated with the market prices, and AIS data were stored into a data warehouse, a dedicated collection of subject-oriented, integrated, non-volatile and time-variant data, pre-aggregated for analytical purposes and implemented in a PostgreSQL relational database with the open source platform pgAdmin and PostGIS extension. The analyses were performed by using the free and open source Geographic Information System (QGIS). Through the utilization of Structured Query Language (SQL) the datasets were managed and therefore associated. Then, the three variables were associated on the spatial base and, in order to assess the spatial pattern of efficiency, the variables were classified in Low (L) and High (H). In particular, 5 classes of efficiency were identified (Table S.2.1), where H and L corresponded respectively to over and under 50 tonnes of landing, 100% of fishing effort and 100 thousand euro of economic value.

In order to better analyse the spatio-temporal distribution of the productivity index, the analyses were carried out also at seasonal level and disaggregated per fishing gears (SOTB, LOTB, RAP and PTM). Specifically, for the seasonal analysis, we considered two classes of efficiency (L and H), different respect to the annual, with values under and over 25 tonnes of landing, 50 % of fishing effort and 50 thousand euro of economic value respectively.

2.2.3 *Target Species*

In order to better explain the fishermen behaviour and the bio-economic spatial pattern, six of the most remunerative target species were selected by analysing the landing compositions of the most remunerative areas. In particular, *Sardina pilchardus* (sardine), *Engraulis encrasicolus* (anchovy), *Sepia officinalis* (common cuttlefish), *Solea solea* (common sole), *Eledone moschata* (musky octopus) and *Aequipecten opercularis* (queen scallop) were selected to carried out high-resolution maps of catches distributions (1x1 km). Since the catches were linearly distributed along the fishing tracks, the spatial distribution of the main target species should be considered approximative.

2.2.4 *Case studies*

The so-called ‘Sole Sanctuary’, a spawning area for soles (Scarcella et al., 2014), and the recent Site of Community Importance (SCI), established in the nearby of the Po River Delta to protect dolphins and turtles, were selected as case studies (**Figure 2.1**). Since the Sole Sanctuary was relocated in the past years, we considered both the old and the current site. Data of landing, economic value and fishing effort recorded in these areas were estimated on a spatial base (cells of 1 km^2).

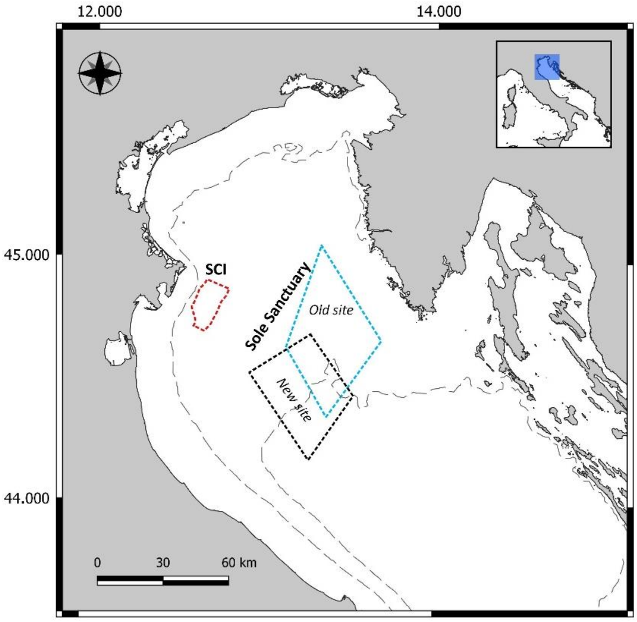

Figure 2.1. Sole Sanctuary (Old and New Site) and Site of Community Importance (SCI).

2.3 Results

2.3.1. Annual trends

The annual spatial distribution of landing (tonnes), economic value (thousand euro) and fishing effort (expressed as percentage of swept area) of the Chioggia's trawlers (LOA over 15 m) operating in the Italian basin of the Northern Adriatic Sea are reported in **Figure 2.2**.

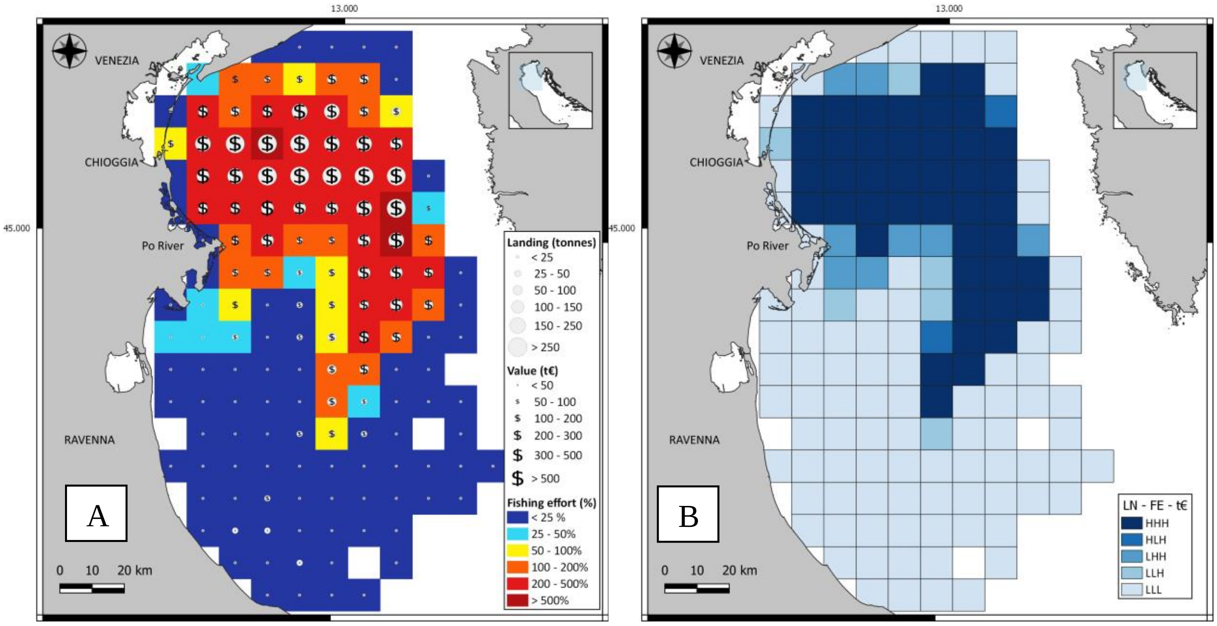

Figure 2.2. (A) Distribution of landings (tonnes), economic value (thousand-euro, t€) and Fishing Effort (FE, expressed as percentage). (B) Aggregation of the three variables classifies as High (H) and Low (L) in the Northern Adriatic Sea.

The analysis, on annual basis, of the spatial distribution of the Chioggia’s trawlers fishing activities (**Figure 2.2A**) highlights a clear pattern with the main fishing grounds localized in the northern and central-eastern basin (fishing effort > 100%). Globally, the fished area (*i.e.*, the area where the trawling activities were recorded) covered 14600 km^2, while the fishing effort, expressed as swept area, was 15487 km^2. Moreover, the total landings, made up of 81 different species, amounted to 8064 tonnes, corresponding to an economic value of about 25 million euro. However, the areas with high values of fishing effort (over 100%) covered just 5100 km^2 (**Table 2.1**), with a swept area of 14352 km^2 (93% of the total fishing effort), 7170 tonnes of landings (89% of the total catches) and an economic value of about 24 million of euro (93% of the whole economic value). Therefore, this area represented the main fishing grounds for the trawlers of Chioggia. Within this area it was possible to further identify a very high productive (landings over 150 tonnes per cell and economic value over 300 thousand euro per cell) and exploited (fishing effort over 200%) sub-area. Overall, in this sub-area 11731 km^2 of swept area (75% of the total fishing effort), 3435 tonnes of fishing products (42% of the total catches) and 18593 thousand euro (77% of the total economic value) were recorded (**Table 2.1**).

Classifying the three variables in ‘High’ (H) and ‘Low’ (L) in was possible to assess the ‘productivity’ of the area (**Figure 2.2._B**). High values of all the three variables (HHH - hot spot area) were widely distributed in almost the whole Northern basin and in the central-eastern area, whereas low values (LLL) were recorded mainly in the southern basin. The ‘hot spot’ area was mainly surrounded by cells with low values of landing but high values of fishing effort and economic value (LHH), only few cells with low value of fishing effort and high value of landing and economic value (HLH), and cells with low values of landing and economic value but high values of fishing effort (LHL).

Table 2.1. Classification of the cells on the basis of the three variables (FE, Landing and Economic value).

Fishing Effort			**Landing**			**Economic value**		
%	N° Cells	km^2	*Tonnes*	N° Cells	*Tonnes*	*€ (1000)*	N° Cells	*€ (1000)*
< 25	79	306	**< 25**	79	596	**< 50**	78	1161
25 - 50	8	280	**25 - 50**	23	817	**50 -100**	9	563
50 - 100	8	550	**50 - 100**	18	1344	**100 - 200**	16	2468
100 - 200	17	2541	**100 - 150**	14	1872	**200 - 300**	11	2687
200 - 500	31	10050	**150 - 250**	4	897	**300 - 500**	14	5734
> 500	3	1681	**> 250**	9	2538	**> 500**	18	12859
Total	**146**	**15407**		**146**	**8064**		**146**	**25472**

In most of the area economic value and landing were proportional in a ratio of about 2:1, being the economic value around twice or more the landings value. However, since the economic value depend on the species composition, in some areas this ratio was not observed.

2.3.2. *Seasonal analyses*

The seasonal maps (**Figure 2.3**) highlighted different patterns of distribution of the three variables. Overall, the widest fishing area was recorded in winter, while the smallest one was in summer. Moreover, the most productive season was autumn, where high values of landing and economic value were widely distributed in the fished area, followed by spring where the variables were concentrated in the northern area. Even if, the fishing effort recorded in summer was lower (1935 km^2) compared to the other seasons (swept area over 4000 km^2), landings and economic value were moderately high.

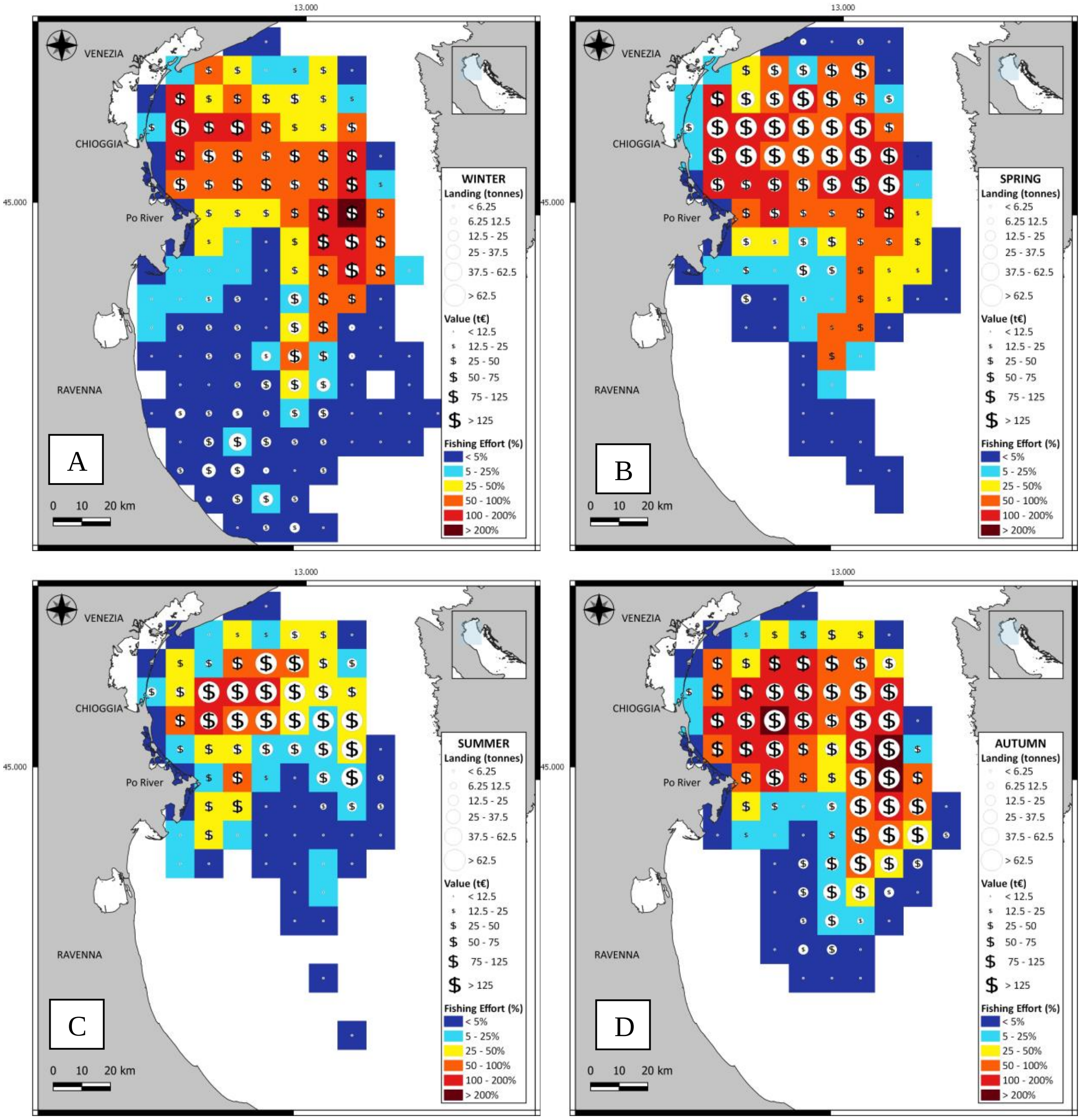

Figure 2.3 Seasonal maps of fishing effort, landing and economic value. A. winter, B. spring, C. summer, D. autumn.

In detail, in winter (**Figure 2.3A**) the fishing activities were distributed in a widest area (13600 km^2), but high values of fishing effort were concentrated in the north and central area, showing two highly exploited fishing grounds (fishing effort > 100%): in the coastal area, between Venezia and Chioggia (500 km^2), and in the offshore area (700 km^2). However, medium-high values of landings (> 25 tonnes) and economic value (> 75 thousand euro) were recorded in these two areas. Moreover, even if in the south the fishing effort was low, medium landings and economic values were recorded. In spring (**Figure 2.3B**) the fishing activities were concentrated in a relatively smaller area, but high values of fishing effort (> 100%) were recorded in 1800 km^2, while very high values of landing (> 62.5 tonnes) and economic value (> 125 thousand euro) were recorded in 1300 and 1700 km^2, respectively. In summer (**Figure 2.3C**) the fished area and fishing effort were lower, with only 400 km^2, located in the coastal area, recognised as highly exploited (fishing effort > 100%). Nevertheless, high values of landing (> 62.5 tonnes) and economic value (> 125 euro) were recorded in 1200 and 1400 km^2, respectively. The highest degree of exploitation was recorded in autumn (**Figure 2.3D**), with high values of fishing effort (> 100%) recorded in 1900 km^2, high values of landing (> 62.5 tonnes) recorded in 1300 km^2 and high economic value (> 125 thousand euro) recorded in 3000 km^2.

As mentioned above, the most productive seasons was autumn with 2578 tonnes of landings and 9452 thousand euro, followed by spring (2331 tonnes and 6124 thousand euro) and winter (1529 tonnes and 5473 thousand euro). However, the fishing effort resulted quite similar in winter, spring and autumn (**Table 2.2**).

Table 2.2. Fished area (FA, km^2), Fishing Effort (FE, km^2), Landing (tonnes), Economic value (thousand euro), ratio between economic value and landings disaggregated among seasons: winter, spring, summer, autumn.

	FA *km^2*	**FE** *km^2*	**Landing** *Tonnes*	**Economic value** *Euro (x 1000)*	**Economic value/landing** *Euro/kg*
Winter	13900	4255	1529	5473	3.579
Spring	10200	4515	2331	6124	2.627
Summer	8000	1935	1624	4426	2.725
Autumn	9300	4708	2578	9452	3.666
Annual	**14600**	**15408**	**8064**	**25475**	**3.160**

In **Figure 2.3** are reported the seasonal maps obtained by matching all the three variables classified as ‘Low’ (L; landing < 25 tonnes, economic value < 50 thousand euro and fishing effort < 50%) and ‘High’ (H; Landing > 25 tonnes, Economic value > 50 thousand euro and FE > 50%). The most remunerative seasons were autumn, spring and winter, recording high values of the economic variable in respectively 40%, 30% e 20% of the total fished area. However, in these remunerative areas, high values of fishing effort and landings were recorded in spring and autumn. In winter these areas were characterized by high fishing effort but low quantity of catches, highlighting the presence of species with high commercial values. The main fishing grounds were localized in the Northernmost area, the area nearest to the homeport, and, restricted to winter and autumn, also in the central-eastern area.

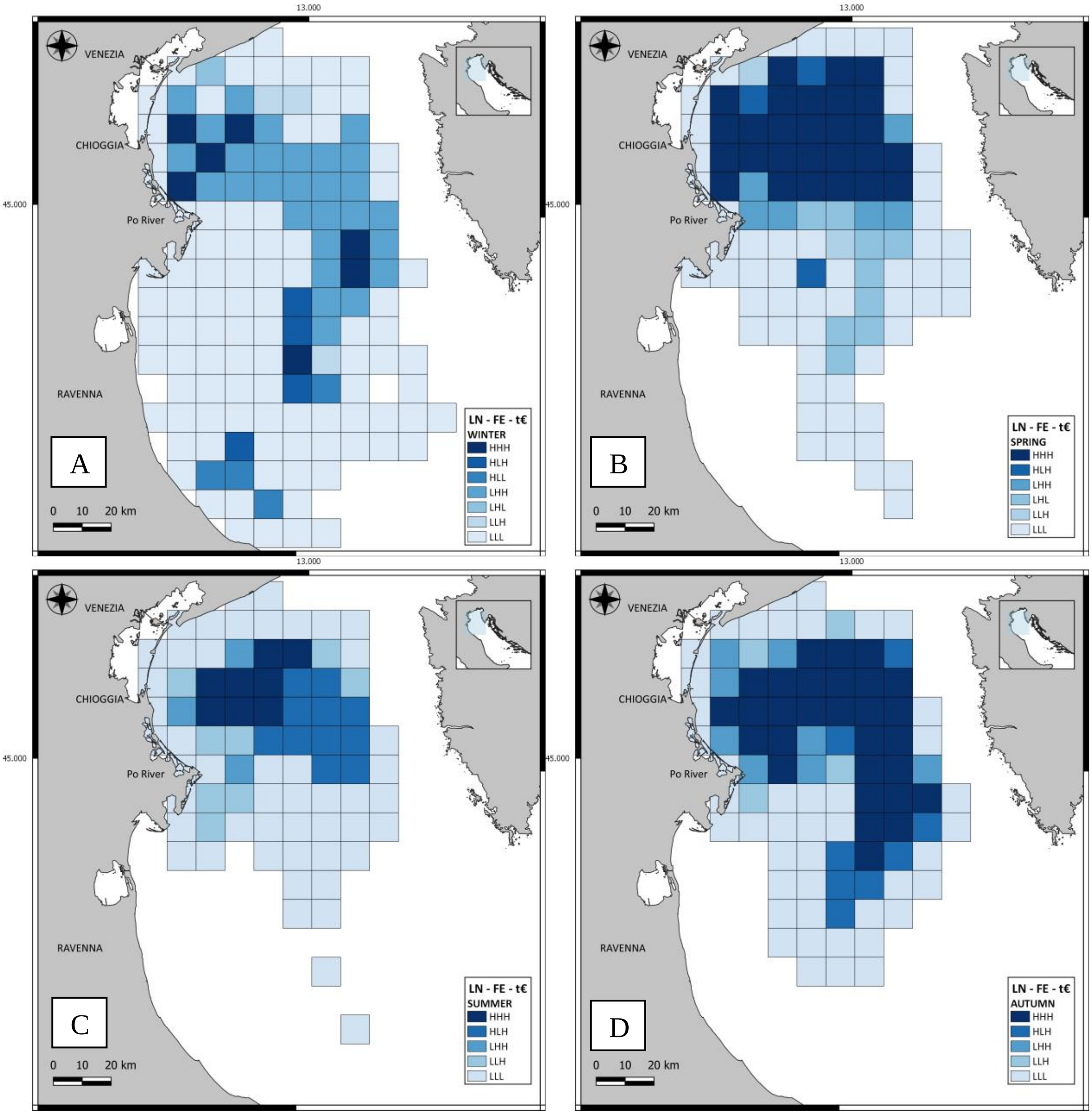

Figure 2.4. Seasonal aggregation of the Landings (LN), Fishing Effort (FE) and economic value (t€) classified as High (H) and Low (L). A. winter, B. spring, C. summer, D. autumn

2.3.3 *Analysis per fishing gears*

The analyses carried out comparing the four fishing gears (SOTB, LOTB, RAP and PTM) highlighted that the fishing effort produced by RAP resulted very high (9839 km^2), followed by LOTB (3140 km^2), PTM (1488 km^2), and SOTB (941 km^2; **Table 2.3**). On the contrary, the gear with the highest quantity of catches resulted PTM, with 6262 tonnes, followed by RAP, LOTB and SOTB which together catches around 1800 tonnes. The economic value resulted comparable for PTM and RAP (around 10 million euro each), while the LOTB and SOTB gained respectively 4 million and 889 thousand euro. The ratio between economic value and landing highlighted highest values for RAP, followed by SOTB, LOTB and PTM.

Table 2.3. Fished area (FA, km^2), Fishing Effort (FE, km^2), Landing (tonnes), Economic value (thousand euro), ratio between economic value and landings disaggregated among seasons and fishing segments: Small Bottom Otter Trawl (SOTB), Large Bottom Otter Trawl (LOTB), *Rapido* Trawl (RAP) and Mid-Water Pair Trawl (PTM).

	FE	**Landings**	**Economic value**	**Economic value/Landing**
	km^2	*Tonnes*	*Euro (x 1000)*	*Euro/kg*
Winter	**4250**	**1529**	**5473**	**3.58**
SOTB	238	25	193	7.86
LOTB	783	102	737	7.21
RAP	2790	401	2679	10.9
PTM	439	1002	1864	1.65
Spring	**4515**	**2331**	**6124**	**2.63**
SOTB	246	22	148	6.66
LOTB	819	101	600	5.91
RAP	2973	276	2299	8.33
PTM	477	1978	3077	1.55
Summer	**1935**	**1624**	**4426**	**2.73**
SOTB	147	24	159	6.65
LOTB	440	111	704	6.35
RAP	1179	194	1610	8.29
PTM	169	1320	1954	1.48
Autumn	**4708**	**2578**	**9452**	**3.66**
SOTB	310	55	388	7.05
LOTB	1098	255	1764	6.91
RAP	2897	391	4103	10.5
PTM	403	1836	3197	1.74
Annual	**15408**	**8064**	**25475**	**3.16**
SOTB	941	126	889	7.06
LOTB	3140	570	3804	6.67
RAP	9839	1106	10690	9.66
PTM	1488	6262	10092	1.62

2.3.4. *Seasonal distribution of the main target species*

The seasonal distribution of the six main target species, selected analysing the landing compositions of the most remunerative areas, were reported in **Figures 2.5, 2.6, 2.7, 2.8 and 2.9**. In particular, *Sardina pilchardus*, *Engraulis encrasicolus*, *Sepia officinalis*, *Solea solea*, *Eledone moschata* and *Aequipecten opercularis* were selected. Since sardines and anchovies shared almost the same distribution area, they were displayed together. It is worth to note that the species distribution, suffering of some limitations, such as the linear distribution of the catches along the fishing tracks is approximative.

As reported in **Table 2.4**, more than the 75% of the total landing was composed by sardines (48.3%) and anchovies (27.3%), which were responsible respectively of the 21.2 and 20.9% of the total economic value.

Table 2.4. List of species (Scientific and common name) with the corresponding quantity (landing), economic value and the ratio between economic value and landing.

Species	**Common name**	**Landing**		**Economic value**		**Economic value/Landing**
		tonnes	%	*euro* (1000)	%	*euro/kg*
Sardina pilchardus	Sardina	3892	**48.3**	5410	**21.2**	1.4
Engraulis encrasicolus	Anchovy	2205	**27.3**	5314	**20.9**	2.4
Sepia officinalis	Cuttlefish	389	**4.8**	3986	**15.6**	10.2
Solea solea	Common sole	395	**4.9**	3782	**14.8**	9.6
Eledone moschata	Musky octopus	230	**2.9**	1295	**5.1**	5.6
Aequipecten opercularis	Queen scallop	139	**1.7**	817	**3.2**	5.9
Squilla mantis	Mantis shrimp	82	**1**	595	**2.3**	7.2
Pecten jacobaeus	Mediterranean scallop	63	**0.8**	571	**2.2**	9.1
Merlangius merlangus	Whiting	116	**1.4**	425	**1.7**	3.7
Loligo vulgaris	Common squid	33	**0.4**	405	**1.6**	12.4
Mullus barbatus	Red mullet	75	**0.9**	359	**1.4**	4.8
Paeneus kerathurus	Striped prawn	17	**0.2**	324	**1.3**	18.9
Alloteuthis media	Midsize squid	9	**0.1**	221	**0.9**	23.4
Bolinus brandaris	Purple dye murex	65	**0.8**	209	**0.8**	3.2
Scophthalmus maximus	Turbot	9	**0.1**	104	**0.4**	11.2
Scophthalmus rhombus	Brill	9	**0.1**	104	**0.4**	11.1
Rossia macrostoma	Shout bobtail	17	**0.2**	201	**0.8**	11.7
Merluccius merluccius	European hake	22	**0.3**	140	**0.6**	6.3
Nephrops norvegicus	Norway lobster	5	**0.1**	123	**0.5**	23.2
Mustelus asterias	Starry smooth-hound	22	**0.3**	113	**0.4**	5
Chelidonichthys lucerna	Tub gurnard	15	**0.2**	92	**0.4**	6.2
Sepia elegans	Elegant cuttlefish	26	**0.3**	87	**0.3**	3.3
Other	Other	227	**2.8**	400	**3.1**	

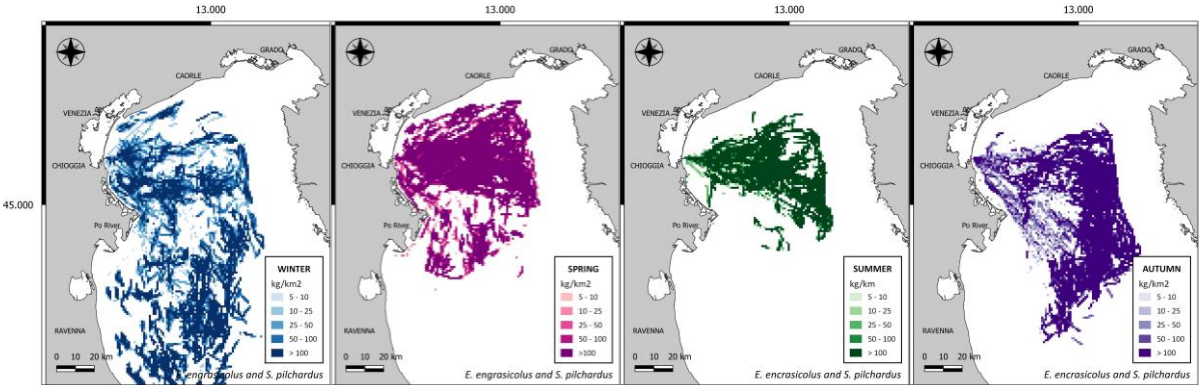

Figure 2.5. Seasonal distribution of the small pelagic fishes *Engraulis encrasicolus* and *Sardina pilchardus*

Small pelagic fishes (*Engraulis encrasicolus* and *Sardina pilchardus*) were the most widespread and abundant species, but their distribution was seasonally different (**Figure 2.5**). Indeed, in winter they were patchy distributed and located also in the southernmost area, while in spring and summer they were mainly concentrated in the northern area, while in autumn the highest density area was mainly located in the most offshore zone.

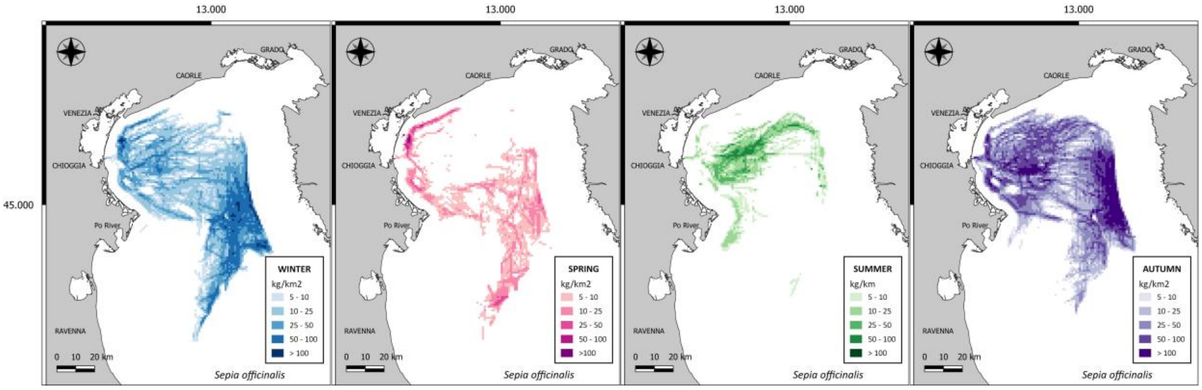

Figure 2.6. Seasonal distribution of the cuttlefish *Sepia officinalis*.

The seasonal spatial distribution of the cuttlefish catches was reported in **Figure 2.6**. Generally, the most productive season was autumn, with two high density areas, one nearest the coast and the other one more offshore, at the border with the Croatian waters. Relatively similar catch areas were recorded also in winter and spring, with the catches more scattered in spring. In summer, the catch area was localized closer to the coast.

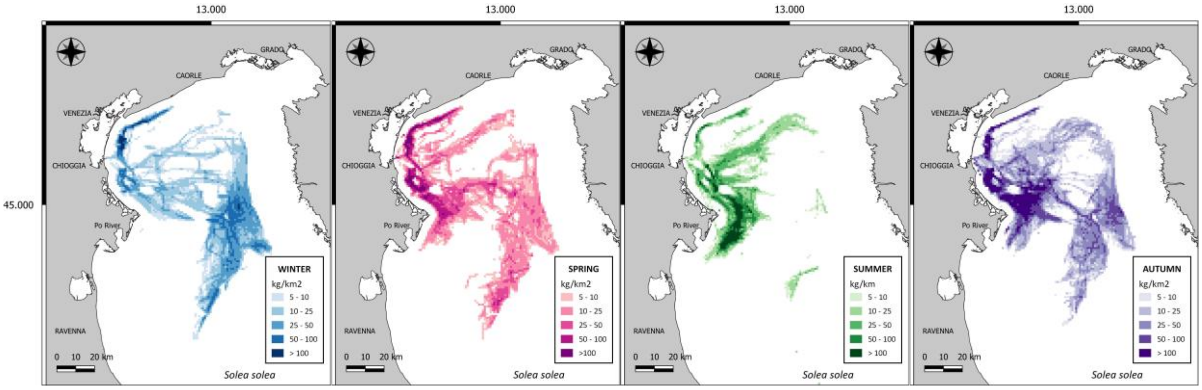

Figure 2.7. Seasonal distribution of the sole *Solea solea*.

Even the catches distribution of the sole *Solea solea* (**Figure 2.7**) highlighted the presence of two main catch areas (coastal and offshore) in winter, spring and autumn. Moreover, in spring, summer and autumn a high-density zone was recorded in the area close to the Po' river estuary.

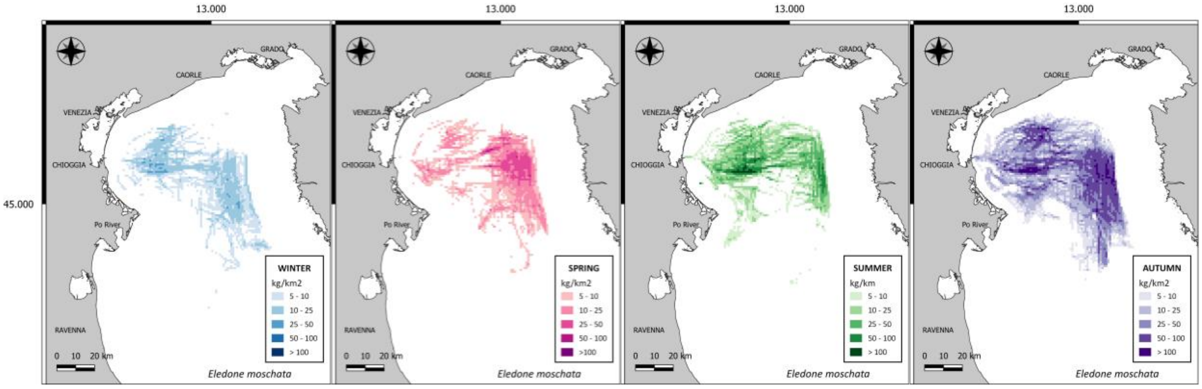

Figure 2.8. Seasonal distribution of the musky octopus *Eledone moschata*.

As highlighted also for other species, the most productive seasons for the musky octopus were autumn and spring, while relative low catches were recorded in winter, during which no high concentration area (>100 kg/km^2) were observed (**Figure 2.8**).

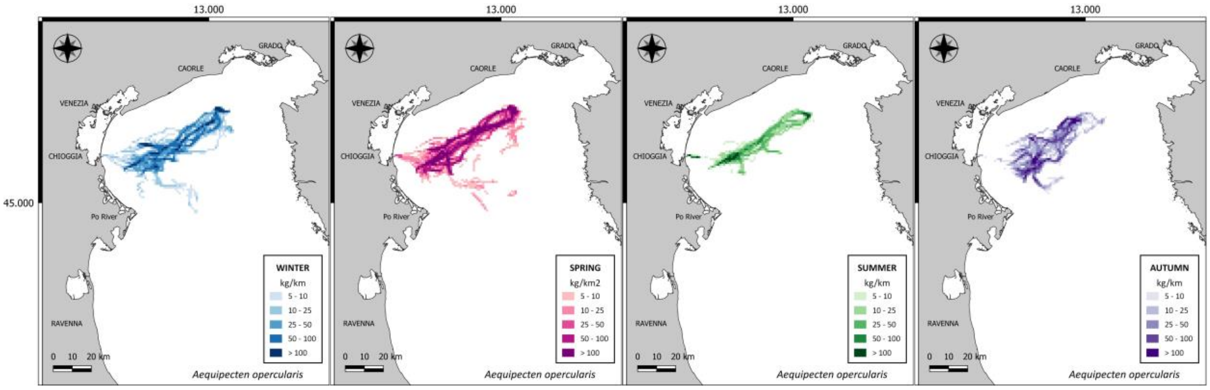

Figure 2.9. Seasonal distribution of the queen scallop *Aequipecten opercularis*.

The maps of the queen scallop catches highlighted well defined and seasonally unvaried distribution areas (**Figure 2.9**), with the highest values observed in spring, localized in the area comprised between Chioggia and Caorle.

2.3.5. *Case studies: Sole Sanctuary and Site of Community Importance (SCI)*

The two sites where the Sole Sanctuary were located, hereafter called New and Old Sites (**Table 2.5**), covered respectively 1368 and 1710 km^2. Overall, they were exploited by the Chioggia trawl fleet in 625 and 621 km^2 with a fishing effort of 320 and 898 km^2, respectively. The fishing effort resulted very high (>100%) in 14% of the New Site and 48% of the Old Site. Moreover, in the New Site 308 tonnes of fishery products were recorded with an overall economic value of 714 thousand euro, while 466 tonnes and 1538 thousand euro were recorded in the Old Site. On average, the catches rate was about 500 kg of products per km^2 in the New Site and 750 kg per km^2 in the Old Site, with an economic value of 1142 and 2476 euro per km^2, respectively.

Table 2.5. Fishing Area (FA, km^2 and %), Fishing Effort (FE, km^2), Landing (tonnes), Economic value (thousand euro) and Price (euro/kg) in the two sites (new and old) recognised as ‘Sole Sanctuary’.

New-Site	**FA**		**FE**	**Landing**	**Economic value**	**Old-Site**	**FA**		**FE**	**Landing**	**Economic value**
	km^2	*%*	*km^2*	tonnes	euro (1000)		*km^2*	*%*	*km^2*	tonnes	euro (1000)
< 10	463	74	17	149	266		127	20	12	62	112
10 – 50	63	10	14	41	78		127	20	31	45	95
50 – 100	13	2	14	11	27		66	11	50	42	99
100 – 200	28	4	52	27	76		128	21	198	96	299
200 – 500	58	9	224	80	267		167	27	561	210	876
> 500	0	0	0	0	0		86	1	45	11	57
	625		**321**	**308**	**714**		**621**		**897**	**466**	**1538**

The Site of Community Importance, recently established, with an area of 225 km^2, resulted exploited by the Chioggia trawl fleet in 179 km^2, with a fishing effort of 167 km^2. In 35% of the fishing area, the fishing effort presented high values (>100%). Overall, 54 tonnes of landing and 196 thousand euro were recorded in this area, with a catches rate of 301 kg per km^2 and an economic value of 1094 euro per km^2 (**Table 2.6**).

Table 2.6. Fishing Area (FA, km2 and %), Fishing Effort (FE, km2), Landing (tonnes), Economic value (thousand euro) and Price (euro/kg) in the Site of Community Importance (SCI).

SCI	**FA**		**FE**	**Landing**	**Economic value**	**Price**
	km²	*%*	*km²*	tonnes	euro (1000)	euro/kg
< 10	37	21	3	6	12	2.0
10 – 50	54	30	16	13	28	2.1
50 – 100	25	14	23	7	24	3.4
100 – 200	52	29	91	23	97	4.2
200 – 500	11	6	34	5	35	7.0
> 500	0	0	0	0	0	
	179		**167**	**54**	**196**	

2.4 Discussions

In the present study, the spatio-temporal assessment of the trawl fishing activities was carried out in a well-recognised overexploited area, the Northern Adriatic Sea, by using an integrate index that combined landing, economic value and fishing effort.

The fishing activities of the Chioggia trawl fleet resulted aggregated in an area of the northern-central basin, where the 93% of the total economic value were gained. This could be expected to continue to produce a high exploitation rate with implication for recruitment and recovery time of fish stocks. Therefore, without the re-allocation of the fishing effort we could assist in the near future to a fishing stock collapse (Colloca et al., 2013, 2017).

The analyses of the fishing productivity revealed that most of the northern part of the area was highly exploited, with high landing and economic value, while the southern basin, more distant from the homeport, resulted low exploited, with low landing and economic value. These latter results can be related with the main target species of that area (*i.e.*, sardine and anchovies) which were distributed homogenously in a wide area. Due to the presence of species with high economic value, as well as the proximity with the homeport, the fishing activities were mainly located in the central-eastern area, where the fishermen can have more income having less direct expenses, for example in terms of fuel consumption. High values of the three variables (HHH) could indicated the presence of over-exploited areas where the fishing stock could collapse soon, while areas where the landing resulted low with high fishing effort and economic value (LHH) highlighted catches of species with high commercial values (*e.g.*, common sole and queen scallop). Differently, the areas with low fishing effort and high landing and economic value (HLH) could indicate restocking areas because the reduction of the fishing effort could have favoured the recovery of the fishing communities. The LLL areas, where all the variables presented low values, were mainly related with the fishing of small pelagic species in winter, while LHL areas were probably exploited in the past and this is in line with the historic fishing behaviour pattern. Indeed, despite low landings and economic value the fishermen concentrated their activities in these areas which resulted with a relative high fishing effort.

The most profitable areas, assessed through the ratio between economic value and landing, were identified in the coastal zone, mainly in areas close to Venice and near the Po River outlet, and in the more offshore area at the bounder with the Croatian water. This was due to the main target species recorder in these areas, in particular cuttlefish, common sole and musky octopus, which have high commercial value. Otherwise, the areas where the ratio between economic value and landing was low, were mainly populated by small pelagic fishes, such as anchovy and sardine, which were very abundant but with low commercial value. Moreover, the more profitable areas were located in the northern zone where, despite the high fishing effort, high economic value and landing were recorded.

Concerning the seasonal analyses of landing, economic value and fishing effort, our results highlighted that in winter the fishing activity was widely distributed with low economic value. This was presumably due to the wide distribution area of the sardine and anchovies. In spring it was possible to highlight a more concentrated distribution of the fishing activity in the central area, probably in response to the species distribution around area with the high primary production. In the summer map the effects of the seasonal fishing ban resulted evident but, at the same time, the economic value was relatively high. This was probably due to capture of species with high commercial value, in particular cuttlefish, common sole, musky octopus and queen scallop. In autumn, the pattern distribution of the three variables resulted comparable to the spring distribution. However, the area interested by high values of all the variables was wider and extended in the central-eastern area, in the nearby of the Croatian economic exclusive zone. This fishermen behaviour could be related to good weather condition and to the presence of target species, such as anchovies, sardine, musky octopus and cuttlefish.

The analyses performed for the four fishing gears (SOTB, LOTB, RAP and PTM) highlighted PTM as the most efficient gear, in relation to the three variables. Indeed, even if similar economic value were recorded for PTM and RAP (about 10 million euro), higher value of fishing effort was recorded for RAP (9839 km^2). However, due to its target species having high commercial values, RAP resulted the gear with the best ratio between economic and landing values, while this ratio resulted worst for PTM, generally used to mainly catch small pelagic species which have low commercial value. Indeed, the mean price per kg of product was lower for PTM (1.62 euro/kg) and higher for RAP (9.66 euro/kg).

Despite the low economic values of sardines and anchovies, around the 75% of the total landings were formed by these species. The high catches of small pelagic species were mainly due to their high abundance in the Adriatic Sea (Piccinetti et al., 2012), but also for the fishing method (*i.e.*, the use of echosounder). Indeed, since the introduction of PTM in the Adriatic Sea the catches of small pelagic fishes increase rapidly (Cingolani et al., 1996). On the contrary, despite the low quantities, cuttlefish and common sole resulted the most profitable species, thanks to their highest market prices. The cuttlefish distribution estimated in this study resulted partially in accordance with Piccinetti et al., (2012) where the authors mapped the maximum distribution along the coastal areas up to 30 meters of depth, while our results revealed a high concentration also in the offshore area. The maximum distribution of cuttlefish mapped by other authors (Piccinetti et al., 2012) overlapped only with our summer map, but probably this was due to the survey period carried out exactly in this season. Despite the already cited limitations of the method, this result points out the importance and novelty of our study, performed at high spatial and temporal resolution, which allowed us to estimate a more precise distribution of the fish stocks. Indeed, according to Belcari et al (1998), the catches of cuttlefish show large seasonal differences with peaks in the autumn and winter, during which cuttlefish reach the coasts for the reproduction (Mandic, 1984).

The common sole distribution reported in this study resulted in accordance with previously published papers (Giovanardi 1984; Piccinetti and Giovanardi, 1984) and also with more recent ones (Grati et al., 2013; Scarcella et al., 2014) where the segregation of this species has been observed in relation to the ages. Indeed, the oldest studies highlighted that the highest abundance was recorded in the nearby of the Po River outlet and in front of the Venice lagoon, while in Grati et al. (2013) and Scarcella et al. (2014), whose researches were brought in late autumn-winter months within the scientific survey SoleMon, the coastal area was mainly populated by youngest soles (under 3 years) and in the offshore areas were concentrated the oldest ones (from 2 to over 5 years). These authors pointed out the importance of this target species, estimating that about the 23% of the total catches of common sole of the entire Mediterranean Sea come from the GSA 17.

The seasonal distribution of musky octopus, the only species of the genus *Eledone* located in the Northern Adriatic Sea, highlighted the highest concentration of organisms in the north-eastern part of the study area, in accordance with previous studies (Manfrin Piccinetti and Rizzoli, 1994; Casali et al., 1998).

The distribution of queen scallop resulted constant both under temporal and spatial perspectives, and the low catches values recorded in summer were related with the fishing ban.

In the past years this species was exploited in the Northern Adriatic Sea as a by-catch of *Pecten jacobaeus* (Mattei and Pellizzato, 1996) but, since 1997 these catches decreased considerably, passing from 803 tonnes to 47 tonnes in 2004, while after this year the queen scallop catches started to constantly increase with values from 57 tonnes up to 190 tonnes in 2016.

Concerning the sole sanctuary, the Chioggia fishing fleet exploited only one half of the total area because, as reported by previous studies (Grati et al., 2013; Scarcella et al., 2014; Bastardie et al., 2017; Santelli et al., 2017), there is a high concentration of bryozoans (*e.g.*, *Amathia semiconvoluta*; Salvalaggio et al., 2014), which makes the seabed untrawlable for the risk to obstruct the nets, and the high presence of holothurians (*e.g.*, *Holothuria forskali* and *Parastichopus regalis*), characterized by the capacity to eviscerate their internal organs under stress conditions, makes the fishery resources less saleable (Bastardie et al., 2017). Comparing the old and new localization of sole sanctuary, catches and economic value resulted higher in the first one, hence under a possible conservation enforcement measure, these differences should be taken into account.

The recently established SCI in the nearby of the Po River outlet could represent in the future on one side an important conservation area for dolphin and turtle, but on the other side an economic loss for the fishermen. Indeed, in this area high economic value per km^2, probably due to high abundance of common soles, were recorded.

Spatial distribution of the main target species in the Adriatic Sea has been already performed at large spatial scale by using data of scientific surveys, in particular MEDITS (Piccinetti et al., 2012) and SoleMon (Adriamed, 2011). However, since these scientific surveys were carried out once in a year (late spring-summer for MEDITS and late autumn-winter for SoleMon) and in limited sites, they did not provide details about the seasonality of the species distribution. On the other hand, they supply valuable information, such as size and sexual maturity of the species, fundamental for the stock assessment. Therefore, our approach may present some advantages compared to scientific surveys, as well as to long time series analysis of the landings, where information about the spatial distribution of the catches are not provided, or the utilization of logbook data, which utilization is limited due to falsification, misreporting and incompleteness issues (GFCM, 2009; STECF, 2013; Damalas, 2015). Indeed, our approach allowed to produce seasonal high spatial resolutions maps of catches distribution though the association of landing data and high-frequency AIS data. Nevertheless, it is important highlight also the limitations of this method, such the assumption of a uniform catch distribution, that is a simplification of the real distribution, or the lack of AIS data before the 2015 and for the vessels under 15 m of LOA. Therefore, the integration of different methodologies might be the best solution to reach a complete overview of the fishing activities and assessing the past, current and future fishery managements.

Despite its limitations, our approach could be very useful in support of the fishery management, for example in the case of the overexploitation of the small pelagic fishes, a challenging issue in the Mediterranean Sea in general and in particular in the Adriatic sub-basin. Indeed, different management strategies were recently proposed, such as the current Ministerial Decree 172 of 30th April 2019, amending the one of 25th January 2016, which established a multiannual plan that includes limits on the number of the fishing days for small pelagic fishes in Mediterranean Sea (max 20 days at months and 180 at year), and specific regulations for the Adriatic Sea (GSA 17 and 18), such as the three-year plan providing limitation of the fishing days for anchovy and sardine (144 day), as well as the total amount of small pelagic catches which must not exceeded the catches recorded in 2014, or the interdiction of these activities within a distance from 6 nm from the coast for several months. Clearly, these regimentations need to be monitored in time and space, as well as the resulting effects should be assessed under environmental, social and economic point of views, and it is in this context that our approach could be very useful.

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Appendix II

Table S.2.1. Classes of efficiency

	Landing	Fishing Effort	Economic value
LLL	L	L	L
LLH	L	L	H
HLH	H	L	H
LHH	L	H	H
HHH	H	H	H

LLL: low landing (< 50 tonnes) - low fishing effort (< 100%) - low economic value (< 100 thousand euro)

LLH: low landing (< 50 tonnes) - low fishing effort (< 100%) - high economic value (> 100 thousand euro)

HLH: high landing (> 50 tonnes) - low fishing effort (< 100%) - high economic value (> 100 thousand euro)

LHH: low landing (< 50 tonnes) - high fishing effort (> 100%) - high economic value (> 100 thousand euro)

HHH: high landing (> 50 tonnes) - high fishing effort (> 100%) - high economic value (> 100 thousand euro)

Chapter 3. Carbon dioxide (CO_2) emissions and intensity of the Northern and Central Adriatic trawling fleet (GSA 17)

Abstract

In this paper the environmental impact, in terms of fuel consumption and CO_2 emissions, produced by fishing trawlers with a length overall (LOA) over 15 m and operating in the Northern and Central Adriatic Sea (GSA17) was estimated. The Automatic Identification System (AIS) was used to get information about the distribution of the fishing vessels and the time spent for fishing and navigation, essential data for the estimation of fuel consumption and to geographically localize the main emission areas. The estimation of the emission intensities for the main species groups (kg CO_2 per kg of catches) was carried out by coupling position data at sea with landing data per day and per vessel. Obtained results highlighted that about 180 thousand tonnes of CO_2 (about 0.09 % of the CO_2 emissions assessed for the worldwide fishery sector) were annually released both in 2015 and 2016, with an average emission intensity of 2.7 kg CO_2 per kg of landing. Performing the analyses on fishing segments basis allowed to evaluate the environmental impact of each gear, highlighting their different efficiency level. Overall this work enriched the emission inventories and provided useful information in a context of fishery management and marine strategy for the implementation of the Ecosystem Based Fishery Management (EBFM) approach in the Adriatic Sea.

3.1. Introduction

The importance of the fishery sector, both in social and economic terms, as well as its criticality, is widely recognised. Indeed, if on one side fishing activities are crucial for human nutrition, as well as source of employment and income, on the other side they contribute to several environmental impacts. Among them, Greenhouse Gases (GHG) emissions, mainly related to fuel consumption, which in turn depends on many factors (*e.g.*, target species, fishing method, type of gear, distance between harbour and fishing ground, main power of the vessel, speed, etc…) represent one of the main issues related to this sector (Tyedmers et al., 2001; Driscoll and Tyedmers, 2010; FAO, 2012; Coello et al., 2015). Since the industrial revolution, GHG emissions are responsible of the global warming, and nowadays their reduction is one of the most important global challenge in order to keep the temperature rise well below 2°C, as established in the Paris Agreement adopted by the United Nations Climate Change Conference (COP21). To date, 185 parties of 197 have ratified the agreement, which entered in force on 4th

November 2016, with the intent to "*combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future*". In the fishery sector, some efforts have been made to move forward a fuel consumption reduction, and therefore to decrease the GHGs emissions, such as the installation of a new magnetic device (Sala and Notti, 2014), the suggestion to change the fishing behaviour (*e.g.*, speed reduction, steeper cuttings in the wings and bellies, increase of mesh size of the net; Sala, 2002; Fiorentini et al., 2004; Parente et al., 2008; Sala et al., 2008; 2011) and the creation of an energy audit system for the fishing vessels (Buglioni et al., 2011). However, the implementation on a global scale of these new approaches is still lacking. Within this context, the emissions inventories could be useful for scientific purposes and also for policy makers, in order to monitoring the emissions and develop new strategies and policies act to achieve a more sustainable fishery.

Currently, emission inventories, mainly related to carbon dioxide (CO_2) which represents the highest percentage of GHG emissions from the fuel combustion (IPCC, 2006; Park et al., 2015), were produced on large scale for the fishery sector (*e.g.*, Tyedmers et al., 2005; Cheilari et al., 2013; Parker et al. 2018; Greer et al., 2019). However, to date, relative few studies were performed at national and regional basis (*e.g.*, Ziegler and Hansson, 2003; Schau et al., 2008; Iribarren et al., 2010; Ziegler and Hornborg, 2014; Coello et al., 2015; Damalas et al., 2016; Laso et al., 2018) and, in order to have a more accurate spatio-temporal evaluation of the GHGs emission related to the fishing activities, the implementation of these studies is becoming more and more urgent.

The global emissions estimated for the fishery sector amounted at 134 million tonnes of CO_2 in 2000 (Tyedmers et al. 2005; FAO, 2012) and 179 million tonnes of CO_2-equivalent in 2011 (Parker et al., 2018). More recently, Greer et al. (2019) estimated that 207 million tonnes of CO_2 were released into the atmosphere in 2016 by marine fishing vessels (159 million tonnes for the industrial fishery and 48 million tonnes from the small-scale fishery). In Europe, it was estimated that 10 million tonnes of CO_2 were realised in 2008 by the European fleet, responsible for a considerable part of the worldwide GHGs emissions. Different methods were used to estimate the fuel consumption and the relative CO_2 emissions, including fuel-based method, which use fuel data provided by fishing vessel operators, and activity-based method, using geospatial data of fishing vessel (Coello et al., 2015). In literature, only few studies estimated the fuel consumption and the CO_2 emissions of the fishing vessels by using geospatial technologies, such as Vessel Monitoring System (VMS) data (*e.g.*, Ziegler et al., 2016) or Automatic Identification System (AIS) data (*e.g.*, Coello et al., 2015; Yao et al., 2016; Chen et al., 2017). In particular, the AIS-based method, a bottom-up process based on the movement of single vessel, is the most advanced and accurate method for the estimation of high-spatial resolution emission inventories (Coello et al., 2015; Smith et al., 2015; Li et al., 2016).

The aim of this work was to produce annual (2015 and 2016) CO_2 emissions inventories for the Northern and Central Adriatic (GSA 17) trawler fleet by using AIS data and discriminating among fishing segments. Indeed, even if the GSA 17 has been recognised as intensively exploited (Barausse et al., 2009; Pranovi et al., 2015; Fortibuoni et al., 2017) and characterized by intensive marine traffic (Ferraro et al., 2007; Spagnolo et al., 2017; Rak et al., 2018), to date no emissions inventory related to the fishing activities were produced in this basin. Moreover, in this area the AIS data have a very high spatio-temporal coverage (75-100%; Blue Hub tool of the Joint Research Centre) which guarantees the high resolution required to estimate, at the best of our knowledge, the CO_2 emissions in this area. Moreover, the landing data of the Chioggia Fish Market (Northern Adriatic Sea, Italy), coupled with the fishing vessel emissions, were used to estimate the emission intensity (*i.e.*, emissions per unit of catches; *sensu* Gerber et al., 2013) for the main landed groups (kg CO_2 per kg of landing) under the integrated holistic approach required by the Ecosystem Based Fishery Management approach.

3.2. Materials and Methods

3.2.1. *Study area and fishing fleets*

The Northern and Central Adriatic Sea (FAO Major Fishing Area 37.2.1; FAO Geographical Sub-Area [GSA] 17), located in the Central Mediterranean Sea, is characterized by intense maritime traffic (Ferraro et al., 2007; Spagnolo et al., 2017; Rak et al., 2018) and intense fishing activities (Barausse et al., 2009; Pranovi et al., 2015; Fortibuoni et al., 2017). The studied area covered 74965 km^2 and was referred to Italian, Croatian and Slovenian waters.

The GSA 17 fleet, which is multi-gears and multi-species, in 2015 was composed by more than 5000 Italian (51%), Croatian (48%) and Slovenian (1%) fishing vessels belonging to different fishing segments (data extrapolated from the European Fleet Register and the Data Collection Framework-DCF): Small-Scale fishery (65%), Bottom Otter Trawl (OTB; about 18%), Dredgers (about 10%), Purse Seines (4%), Midwater Pair Trawl (PTM; about 2%) and *Rapido* (RAP; 1%).

In this study, only trawlers with a LOA over 15 m were taken into consideration (**Table 3.1**), and in particular: Small (SOTB, LOA < 18m) and Large (LOTB, LOA > 18m) OTB, RAP (a kind of Beam Trawler typical of the Adriatic Sea called *Rapido*) and PTM (*Volante*).

Table 3.1. Number of trawlers considered in this study.

	2015	2016
LOTB	312	296
SOTB	141	151
PTM	94	98
RAP	69	70
GSA17	618	617

3.2.2. *AIS data*

The terrestrial Automatic Information System (AIS) raw data, based on the transmission of very high frequency (VHF) radio signals, was provided by the Italian Coast Guard (ITC and Traffic Monitoring Department – Rome) and played a key role in this work. These data, constituted by around 922 million positions issued by Adriatic trawlers operating in the GSA 17 between January 2015 and December 2016, provided several information essentials for the analysis. In particular, some dynamic information (such as ship's positions, time and speed) were used to discriminate the vessels activities (*i.e.*, fishing and navigation) and reconstruct the trajectories, while static ones (such as Maritime Mobile Service Identity [MMSI], Ship's Name and International Radio Call Sign [IRCS]) were used for the vessels' identification.

3.2.3. *Fuel consumption and CO_2 estimation*

The fuel consumption (FC) of each fishing vessel was estimated applying the equation (Equation 3.1) reported by Prado (FAO, 1990):

Equation 3.1 $$\boldsymbol{FC = a * P_{(max)} * \frac{S}{d} * t * 0.001}$$

where

a = average coefficient (ranging between 0.5 and 0.8)
$P_{(max)}$ = maximum engine power (kW)
S = specific fuel consumption expressed in g/kW/h
d = density of fuel (0.86 kg/l)
t = hours (h) of fishing or navigation

The average coefficient, corresponding to the percentage of engine power used, was fixed at

0.75, as reported in Prado (1990). The specific fuel consumption was set at 188 g/kW/h for fishing and 150.4 g/kW/h for navigation phase (Lee et al., 2018), and the engine power ($P_{(max)}$) has been assessed for each vessel according to the database. In order to test the formula (Eq.1), values of fuel consumption, expressed in l/h and relative to fishing and navigation, were extrapolated from literature (Sala et al., 2011; Buglioni et al., 2011; Marlen et al., 2014) and recalculated using the Equation 3.1 (Supplementary **Table. S3.2**), highlighting the high correspondence between the real and the estimated values.

The basic method Tier 1 (IPCC, 2006; Park et al., 2015; Parker et al., 2018) based on the following equation (Equation 3.2), was used for the estimation of the CO_2 emissions:

Equation 3.2 $$\boldsymbol{CO_2\ Emissions} = \sum(\boldsymbol{Fuel\ Consumed} * \boldsymbol{Emission\ Factor})$$

The fuel consumed and the emission factor depends on the type of fuel, of which the marine diesel is generally the most common in the fishing vessels (Greer et al., 2019), with a carbon content of about 86.7% (Klein et al., 2012). The emission factor used in the present study was 3.179 kg CO_2 per kg of fuel (Cooper and Gustafsson, 2004; Greer et al., 2019), corresponding to 2.86 kg CO_2 per litre of fuel combusted (Parker et al., 2018).

3.2.4. *Data analysis*

3.2.4.1. Fuel consumption and CO_2 estimation

Considering the high amount of AIS data signals, the dataset was implemented in a PostgreSQL relational database with the open source platform pgAdmin and PostGIS extension. Prior to the analyses, the vessels were identified by merging the International Radio Call Sign (IRCS) and the ship's name of the AIS data with the data reported in the European Fishing Fleet's Register, which provides several information (*e.g.*, LOA, engine power [kW], primary and secondary gear). Since some errors, such as misspelled IRCS or ship's names, occurred in the EU Fleet's Register, also the Marine Traffic website was used to improve the accuracy of the vessels' identification. Moreover, the modal value of the speed frequency distribution of each vessel was used to check the gears, by considering the speed range, peculiar to each fishing segment (Natale et al., 2015). Furthermore, in order to detect possible switches of the gears the Chioggia trawlers were checked in the harbour and an accurate evaluation of the landing data (check of the main target species of the fishing gears) was carried out.

The AIS data was used to reconstruct the trajectories of the trawlers and extrapolate the hours of fishing and navigation phases, essential to estimate the fuel consumption. Specifically, the data were linearly interpolated considering all the points recorded for each vessel, from the exit to the return in port, and the trajectories were reconstructed, adding information relative to the activities. In particular, the vessels speed profile of each fishing gear (SOTB, LOTB, RAP and PTM) was used to classified five phases: 0=in port, 1= exit from the port, 2= entry in port, 3=fishing, 4=navigation. Once extrapolated the hours of fishing and navigation and considering the engine power (kW) of each trawler, the Equation 3.1 was applied to estimate annual and seasonal fuel consumption (l/h). Finally, the latter was multiplied per the specific emission factor (2.86 kg CO_2 per litre of fuel) converting the fuel consumption in CO_2 emission. The 2015 and 2016 total emission, together with the annual (CO_2/v) and daily (CO_2/v/day) emissions per vessel (tonnes), and the incidence of each fishing segment to the total CO_2 emissions, were estimated.

3.2.4.2. *Emission intensity*

In order to estimate CO_2 emissions per unit of landing, the sub-set of AIS data relative to the Chioggia Trawl Fleet, one of the main trawler fleets of the Adriatic Sea, was selected and the landing data were uniformly distributed along the fishing tracks of each vessel, considering the landing day and the day of return in port. This distribution was proportional to the length of the fishing segment, but clearly it was a simplification of the real distribution.

Landing data, used to estimate the CO_2 emission for kg of landed products, were collected by the Chioggia Fish Market, located in the Northern Adriatic Sea. For each vessel, the CO_2 emissions and the relative catches quantity (kg) were extrapolated. Since the latter were multispecies, to avoid an over-estimation of the CO_2 emissions, the incidence (expressed in %) of each specie caught by a specific vessel in a specific day, was calculated. Therefore, the CO_2 emitted by each fishing vessel in that day was then multiplied for the incidence of the species, and the result was divided per the catches quantity, obtaining the estimation of kg of CO_2 emitted to catch 1 kg of that species in a given fishing trip. Finally, the ratio between the emissions (kg of CO_2) and the landing quantity (kg), was calculated.

To simplify the results presentation, the target species were classified in 7 groups: Small Pelagic Fishes (S-PF), Big Pelagic Fishes (B-PF), Molluscs with shell (MLS), Demersal Fishes (DF), Flatfishes (FF), Cephalopods (CPH) and Crustaceans (CRS).

Finally, in order to compare the emission intensity of the fish products with the other livestock, the percentage of proteins of each species group has been extrapolated from literature (Roe et al., 2013) and the CO_2 emission per kg of proteins was estimated and compared with the value reported in Nijda et al. (2012).

3.3. Results

3.3.1. *Emission inventories*

The 2015 and 2016 CO_2 total emission (expressed in thousands of tonnes), together with the annual (CO_2/v) and the daily (CO_2/v/day) emissions per vessel (tonnes), and the incidence of each fishing segment to the total CO_2 emissions (CO_2 %) are reported in **Table 3.2**. These data include both fishing (F), navigation (N) and the sum of them.

Table 3.2. Fishing (F), navigation (N) and total CO_2 emissions: annual (CO_2; thousand tonnes), annual per vessel (CO_2/v; tonnes), daily per vessel (CO_2/v/day) and the incidence among fishing segments (%) in 2015 and 2016 for the trawls fleet (SOTB: Small Bottom Otter Trawl; LOTB: Large Bottom Otter Trawl; RAP: *Rapido* trawl; PTM: Midwater Pair Trawl).

2015	**CO_2**	**CO_2/v**	**CO_2/v/day**	**CO_2 %**	**2016**	**CO_2**	**CO_2/v**	**CO_2/v/day**	**CO_2 %**
F	*tonnes* (1000)	*tonnes*	*tonnes*	*%*	F	*tonnes* (1000)	*tonnes*	*tonnes*	*%*
SOTB	11	79	0.48	11		12	81	0.48	11.5
LOTB	63	201	1.22	61.4		65	221	1.34	61.3
RAP	17	253	1.54	17.1		18	256	1.55	16.8
PTM	11	113	0.69	11.5		11	113	0.69	10.4
ALL	**102**	**165**	**1**			**106**	**173**	**1.05**	
	CO_2	**CO_2/v**	**CO_2/v/day**	**CO_2 %**		**CO_2**	**CO_2/v**	**CO_2/v/day**	**CO_2 %**
N	*tonnes* (1000)	*tonnes*	*tonnes*	*%*	N	*tonnes* (1000)	*tonnes*	*tonnes*	*%*
SOTB	14	97	0.59	17.6		15	101	0.61	19.3
LOTB	31	98	0.6	39.2		32	107	0.65	39.2
RAP	12	174	1.05	15.3		12	167	1.01	14.6
PTM	22	232	1.41	27.9		22	221	1.34	26.9
ALL	**78**	**127**	**0.77**			**81**	**130**	**0.79**	
	CO_2	**CO_2/v**	**CO_2/v/day**	**CO_2 %**		**CO_2**	**CO_2/v**	**CO_2/v/day**	**CO_2 %**
Total	*tonnes* (1000)	*tonnes*	*tonnes*	*%*	*Total*	*tonnes* (1000)	*tonnes*	*tonnes*	*%*
SOTB	25	175	1.07	13.9		27	182	1.09	14.8
LOTB	93	299	1.82	51.8		97	328	1.99	51.8
RAP	29	427	2.59	16.3		30	424	2.56	15.9
PTM	33	346	2.1	18		33	334	2.03	17.5
ALL	**180**	**292**	**1.77**			**187**	**303**	**1.84**	

Generally, the hours of fishing and navigation resulted very similar in the two years analysed (**Supplementary Table S3.1**), both considering the whole fleet and the fishing segments. Consequently, the estimation of the fuel consumption (**Supplementary Table S3.1**) and the relative CO_2 emissions resulted stable in the investigated years, with slightly higher values recorded in 2016. The highest CO_2 emissions were recorded during the fishing operations (around 102 and 106 thousand tonnes in 2015 and 2016, respectively), but high levels of CO_2 were recorded also during navigation, with values of CO_2 around 78 thousand tonnes in 2015 and 81 thousand tonnes in 2016. In total, 180 and 187 thousand tonnes of CO_2 were estimated in 2015 and 2016 respectively, for the GSA17 trawl fleet. Since the two years turned out to be very similar, and in order to simplify the text, only the 2016 results are reported in the manuscript.

Among the gears, the main source of CO_2 (96.9 thousand tonnes) was the LOTBs, which represented the most abundant fleet (296 vessels). Even if the lowest quantity of CO_2 was emitted by SOTBs (around 28 thousand tonnes), similar emissions were recorded also for RAP and PTM (30 and 33 thousand tonnes, respectively). However, the annual emissions per vessel of each fishing segment, highlighted the highest values of CO_2 for RAP (424 tonnes per vessel), followed by PTM (334 tonnes per vessel) and LOTB (328 tonnes per vessel), while SOTB remained the smallest producer (182 tonnes per vessel). Moreover, the incidence of the emissions related to fishing and navigation phases were different among the fishing segments (**Figure 3.1**). In particular, emissions caused by fishing phase were higher for LOTB (67%) and RAP (61%), while for PTM the highest emissions were recorded during the navigation phase (66%). The incidence of the two phases were comparable for SOTB with 45% of emissions produced in fishing and 55% in navigation. Globally, the highest percentage of CO_2 was recorded during the fishing phase (57%).

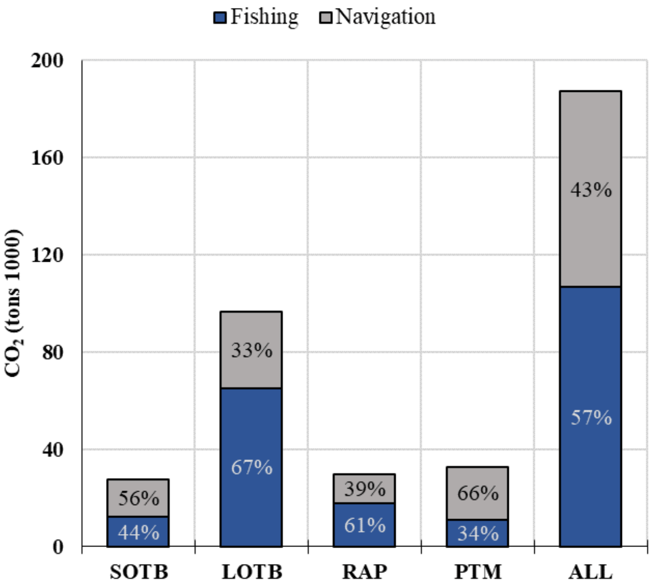

Figure 3.1. Percentage of CO_2 emissions discriminated between Fishing and Navigation of each fishing segments (LOTB, SOTB, RAP and PTM) and the whole fleet in 2016.

The spatial high-resolution maps (1 km^2) of the total CO_2 emissions for the 2016 caused by trawlers in the GSA 17 are reported in **Figure 3.2**. Even if we are aware that this represent an indication of CO_2 emission, our results allowed us to highlight the most impacted areas in the GSA 17. In particular, the highest values of CO_2 were recorded in the Northernmost basin as well as in the Italian coasts.

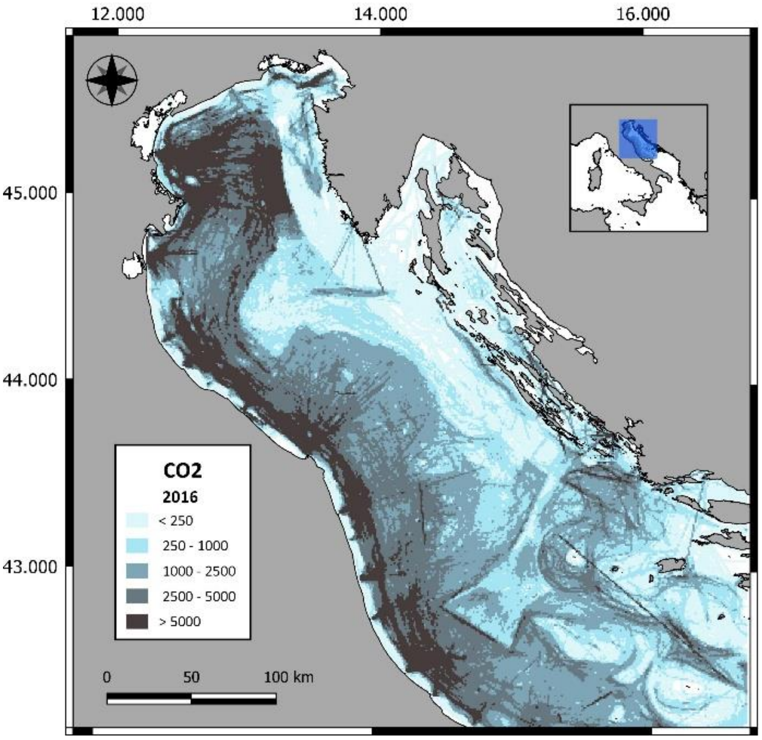

Figure 3.2. CO_2 emissions estimated for fishing and navigation activities in the GSA 17 (2016).

The seasonal CO_2 emissions (thousand tonnes) related to the two phases, and the incidence among the seasons (%), were estimated for each fishing segments and the whole fleet (**Table 3.3** and **Figure 3.3**). Regardless from the gear, the seasonal analyses highlighted that the main emissions of CO_2 were released in autumn (more than 28%) and spring (more than 27%), while the lowest values were recorded in summer (less than 19%).

Table 3.3. Seasonal CO_2 emissions of fishing (F) and navigation (N) and overall (%).

Gear		WINTER		SPRING		SUMMER		AUTUMN	
		tonnes (1000)	%	*tonnes* (1000)	%	*tonnes* (1000)	%	*tonnes* (1000)	%
SOTB	**F**	2.8	21.7	3.3	27	2.1	18.8	3.8	32.5
	N	3.1		3.9		3.2		4.8	
LOTB	**F**	15.5	23.1	18.5	28.4	11.5	18.9	19.2	29.6
	N	6.9		8.8		7.1		9.2	
RAP	**F**	4.7	24.9	5.2	28.2	2.6	18.8	5.3	28.1
	N	2.8		3.3		3		3.1	
PTM	**F**	2.6	23.4	3.0	28.5	1.5	18.6	3.5	29.5
	N	5.0		6.2		4.5		6.1	
GSA 17	**F**	25.5	23.2	30.1	28.2	17.6	18.9	31.9	29.7
	N	17.8		22.2		17.8		23.2	

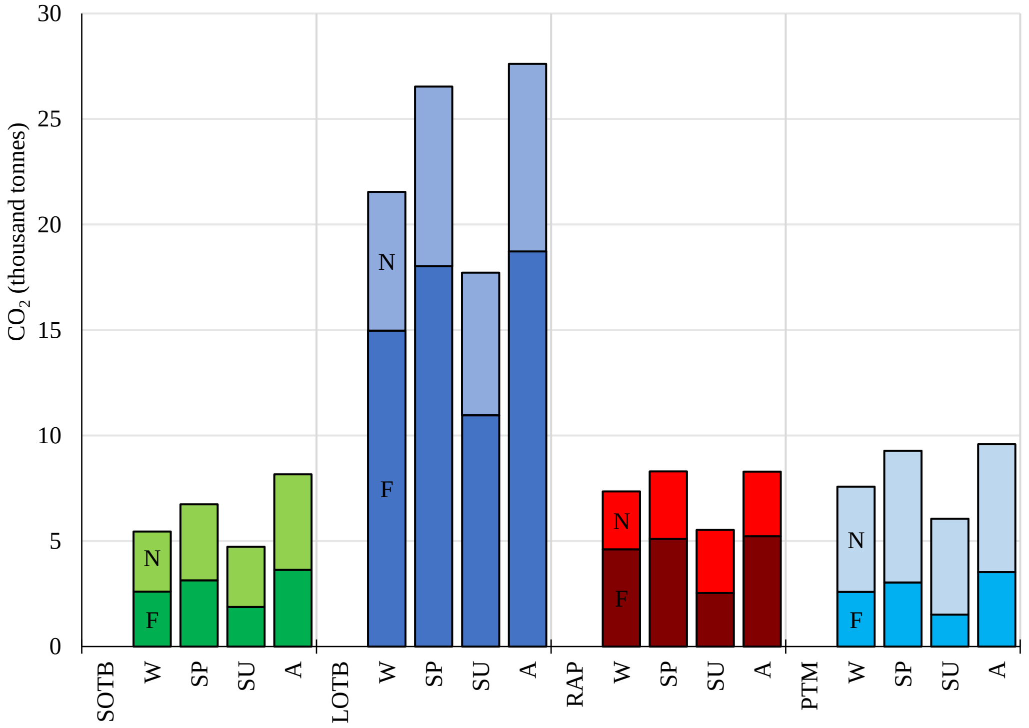

Figure 3.3. Seasonal CO_2 emissions (W: winter; SP: spring; SU: summer; A: autumn) of the different fishing segments in fishing (F) and navigation (N) in the 2016.

3.3.2. *Emission intensity per species*

Total emissions (thousand tonnes), landing (tonnes) and the emissions intensity (kg CO_2 per kg of landing) of the different types of fishing gears of the Chioggia's fleet were estimated for 2015 and 2016 (**Table 3.4**). The mean between the two years and the average CO_2 emission per vessel are reported too. Globally, 22.6 and 23.5 thousand tonnes of CO_2 were emitted to catch 8983 and 8064 tonnes of fishery products respectively in 2015 and 2016 with an average emission intensity of 2.7 kg CO_2 per kg of landing. Differently from the results reported for the whole GSA17 fleet, the main emissions produced by the Chioggia's fleet were due to RAP (on average 11.7 thousand tonnes) and LOTB (around 7.5 thousand tonnes), while on average 3.2 thousand tonnes were emitted by PTM and 0.7 by SOTB. These differences were mainly due to the number of vessels of each fishing segment (32 RAP, 22 LOTB, 16 PTM and 7 SOTB). Generally, the standardized emissions per vessels resulted in line with the ones previously reported for the same fishing segments of the whole GSA17 fleet. In fact, on average the highest rate of emissions was recorded for RAP (366 tonnes per vessel) and LOTB (341 tonnes per vessel), while the emissions rate for SOTB and PTM were lower, with about 100 and 200 tonnes per vessels, respectively.

Table 3.4. CO_2 emissions (thousand tonnes), Landings (Tonnes), and CO_2 intensity (CO_2/landings; kg/kg) estimated for the fleet of Chioggia (LOA>15m).

	CO_2			**Landings**			**CO_2/Landings**			**CO_2/vessel**
	tonnes (1000)			*tonnes*			*kg/kg*			*tonnes*
	2015	**2016**	**Mean**	**2015**	**2016**	**Mean**	**2015**	**2016**	**Mean**	**Mean**
SOTB	0.5	0.9	0.7	83	126	105	6.0	7.1	6.6	100
LOTB	7.4	7.6	7.5	507	570	539	14.6	13.3	14	341
RAP	11.8	11.6	11.7	1262	1106	1184	9.4	10.5	9.9	366
PTM	2.9	3.5	3.2	7131	6262	6697	0.4	0.6	0.5	200
Total	**22.6**	**23.5**	**23.1**	**8983**	**8064**	**8525**	**2.5**	**2.9**	**2.7**	**299**

Considering the ratio between emissions and landings, the lowest value was recorded for PTM (0.5 kg CO_2 per kg of landing), while the highest was for LOTB (14 kg CO_2 per kg of landing), followed by RAP (9.9 kg CO_2 per kg of landing) and SOTB (6.6 kg CO_2 per kg of landing). The analyses performed per groups (CPH: Cephalopods, MLS: Molluscs with shell, S-PF: Small Pelagic fishes, B-PF: Big Pelagic Fishes, DF: Demersal Fishes, FF: Flatfishes and CRS: Crustaceans) landed in 2016 are reported in **Table 3.5**.

Table 3.5. Emission intensity (kg CO_2 per kg landing). (CPH: Cephalopods, MLS: Molluscs with shell, S-PF: Small Pelagic fishes, B-PF: Big Pelagic Fishes, DF: Demersal Fishes, FF: Flatfishes and CRS: Crustaceans).

	SOTB	**LOTB**	**RAP**	**PTM**
S-PF	7.12	14.07	-	0.41
B-PF	6.91	11.41	-	0.32
MLS	-	13.41	9.01	-
DF	6.99	13.83	11.24	1.15
FF	7.12	10.78	10.39	15.37
CPH	7.21	14.54	9.67	11.43
CRS	7.01	15.49	10.21	13.99

The highest emissions intensity was estimated for LOTB (ranging from 10.78 to 15.49) and RAP (from 9.01 to 11.24). Regardless from the groups, the CO_2 produced by SOTB was around 7, while the emissions intensity of PTM ranged from 0.32 to 15.37. Among the landing groups, the highest emissions intensity resulted 15.49 kg CO_2 per kg of crustaceans (caught by LOTB) while the lowest one was 0.32 kg CO_2 per kg of big pelagic fishes (caught by PTM). However, for these landing groups the quantity landed on average per year resulted low, compared to the other groups. For cephalopods, one of the most representative groups for SOTB (56.5 tonnes), LOTB (266 tonnes) and RAP (355 tonnes), the average emission intensity was respectively 7.21, 14.54 and 9.67 kg CO_2 per kg of landing. The second most abundant group for SOTB (35.5 tonnes) and LOTB (207 tonnes) was represented by demersal fishes, showing an emission intensity of 6.99 and 13.83 kg CO_2 per kg of landing. Flatfishes and molluscs with shell caught by RAP, its target species, recorded 464 and 224 tonnes of landing with an emission intensity of 10.39 and 9.01, respectively. Finally, the 97% of the PTM landing was represented by small pelagic fishes (6527 tonnes) for which a very low emission intensity was estimated (0.41 kg CO_2 per kg of landing). The weighted average of the emission intensity of each group (kg CO_2 per kg of landing), estimated by considering the CO_2 emissions and the catches of all the fishing gears, the annual average emissions (tonnes and percentage) and the landings (tonnes and percentage) are reported in **Table 3.6** and **Figure 3.4**. The emission values resulted very low for small pelagic fishes (0.41 kg CO_2 per kg of landing) and high for big pelagic fishes (5.93 kg CO_2 per kg of landing). Compared to the results reported per fishing gears, lower emission intensities were estimated for the other groups, in particular crustaceans, cephalopods and flatfishes (about 11 kg CO_2 per kg of landing). A different incidence of each group in the total amount of emissions and landings was highlighted, and in particular, the main emissions were produced to catch cephalopods (34%) and flatfishes (23%), but the highest percentage of landing (77%) was composed by small pelagic fishes.

Table 3.6. Weighted average of emission intensity, annual average emissions and landings of each landing group.

	Emission intensity	**CO_2**		**Landing**	
	kg CO_2/kg landing	*tonnes*	%	*tonnes*	%
S-PF	0.41	2688	11	6534	77
B-PF	5.93	77	0.3	13	0.2
MLS	9.05	2045	9	226	3
DF	9.28	3947	17	426	5
FF	10.48	5284	23	504	6
CPH	11.38	8039	34	707	8
CRS	11.48	1332	6	116	1

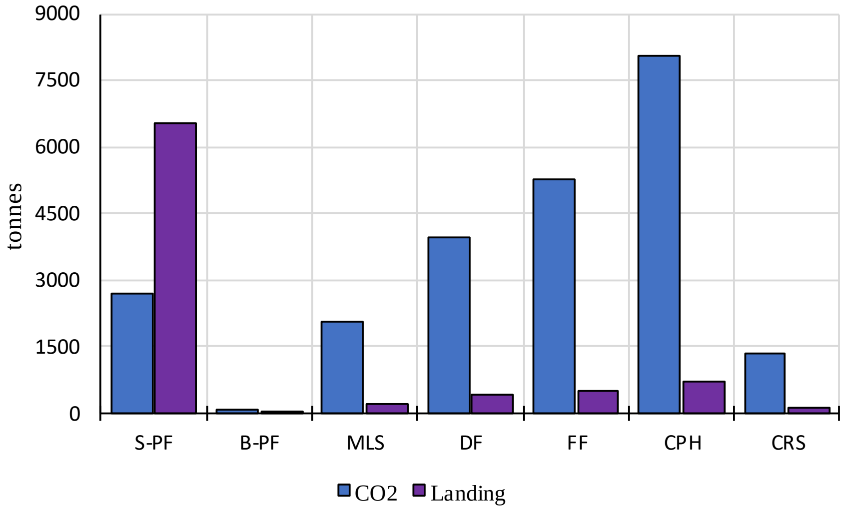

Figure 3.4. CO_2 emissions and landings (expressed in tonnes) recorded for the seven landing groups. (CPH: Cephalopods, MLS: Molluscs with shell, S-PF: Small Pelagic fishes, B-PF: Big Pelagic Fishes, DF: Demersal Fishes, FF: Flatfishes and CRS: Crustaceans).

3.3.3. *Comparison with other protein sources*

The emission intensities of the fish products (converted in kg of CO_2 per kg of protein) ranged from 2.1 kg of CO_2 per kg of proteins (S- PF) to 65 kg of CO_2 per kg of proteins (CPH; **Table 3.7)**. The weighted average value estimated by considering the emissions intensities and the quantity of product landed was 14 kg of CO_2 per kg of proteins.

Table 3.7. Emissions intensity expressed as kg CO_2 per kg of protein of each landing group. (CPH: Cephalopods, MLS: Molluscs with shell, S-PF: Small Pelagic fishes, B-PF: Big Pelagic Fishes, DF: Demersal Fishes, FF: Flatfishes and CRS: Crustaceans).

	Emission intensity
	kg CO_2/kg protein
S-PF	2.1
B-PF	32.9
MLS	50.3
DF	46.3
FF	61.7
CPH	65.0
CRS	60.4

Compared with other sources of proteins (see Nijda et al., 2012) our values resulted similar (*i.e.*, cultured fishes, poultry and pork) or definitely lower (*i.e.*, beef and lamb) compared with the data reported in the literature (**Table 3.8**).

Table 3.8. Emissions intensity expressed as kg CO_2 per kg of protein of each the main animal sources of protein.

	Emission intensity *kg CO_2/kg protein*
Cultured fishes	4 - 75
Poultry	10 - 30
Pork	20 - 55
Beef	45 - 640
Lamb	51 - 750

3.4. Discussions

The aim of this work was to implement the current CO_2 emission inventories for the fishery sector and improve the knowledge of the environmental impact in terms of CO_2 emissions, produced by the trawlers fleet in the Northern and Central Adriatic Sea (GSA17). The AIS-based method here adopted, and based on the movement of single vessels, was described as one of the most accurate for the estimation of high-spatial resolution inventories of emissions (Coello et al., 2015; Smith et al., 2015; Li et al., 2016). To the best of our knowledges, only few studies have been performed to estimate the fuel consumption and the CO_2 emissions by using an AIS-based method (Coello et al., 2015; Yao et al., 2016).

The present work provides useful information related to a very peculiar and overexploited area. However, it is important to recognise that, since the AIS is currently mandatory only for vessels with a LOA over 15 m, the results here discussed are referred to a portion of the GSA17 trawler fleet (about 57%), hence the total emissions were underestimated. However, these results are referred to the most active fleet of the Adriatic Sea, characterized by the most powerful engines, and therefore they can be considered highly representative of spatial and temporal pattern recognised to a quite important emissions source.

Overall, 180 thousand tonnes of CO_2, corresponding to around 0.09% of the global CO_2 emissions (Greer et al. 2019), were estimated on average per year (2015 and 2016) for the Northern and Central Adriatic trawlers. The emissions map highlighted that the main impacted areas were located in the Italian part of the basin, being the Italian trawler fleet the most representative. In general, the fishing phase was more significant than the navigation one in term of emissions, reaching the 57% of the total. This was probably due to the higher engine power that must be exercised to trawl the net. However, disaggregating the results among fishing gears it was observed that the two phases had different importance in relation to the fishing technique, and in particular this difference was evident between bottom trawling and midwater trawling, where the emissions of the latter were mainly due to navigation. These results could be related to the fact that PTM activity is characterized by the active research of school fish, using echosounder and sonar, as well as the wide distribution of the fishing grounds, and consequently the time spent in navigation was higher.

Overall, the impact of the fishing segments in the total emissions was different, and specifically the main annual emissions were caused by LOTB, which represent the major fleet (around 300 vessels) operating in the GSA 17, recording more than 90 thousand tonnes of CO_2, that was around three times the emissions caused respectively by SOTB, RAP and PTM. However, the emissions per vessel pointed out the RAP as the gear causing the highest emissions, and this was probably due to the engine power of the fishing segments, higher for RAP (363±162 kW) and PTM (363±180 kW), medium-high for LOTB (303±141 kW) and lowest for SOTB (169±61 kW). Since the emissions are proportional to the fuel consumption, these results provided also information about the economic impact of the different fishing segments. However, it is worth to notice that the precision of the results is linked to the accuracy of the engine power values (kW) reported in the EU fleet register.

The estimation of the emission intensity, that is the quantity of CO_2 emitted per kg of landed products, allowed us to discriminate the efficiency of each segment. In particular, PTM was recognised as the most efficient fishing gear, recording on average an emission intensity of 0.5 kg CO_2 per kg of landed product, while LOTB resulted the most emission intensive with on average 14 kg CO_2 per kg of landing. These results are in line with the paper published by Parker and Tyedmers (2015), where the author identified the fisheries targeting small pelagic species as the most efficient. Moreover, even the average emission intensity per landing groups was in line with the data reported in literature, and in particular resulted very low for small pelagic fishes, while the catches of flatfishes, cephalopods and crustaceans were confirmed to have the highest carbon footprint (Parker and Tyedmers, 2015; Parker et al., 2018). However, as already highlighted by Parker et al. (2018), the emission intensity of many groups of wild fishes are generally lower compared to the other animal products, such as beef and lamb. In particular, the emissions of CO_2 per kg of protein here estimated ranged from 2 to 65 with a weighted average value of 14, while, comparing our results with literature values (Nijda et al., 2012), similar ranges were reported for cultured fishes (4 - 75 kg CO_2 per kg protein), poultry (10 - 30 kg CO_2 per kg protein) and pork (20 - 55 kg CO_2 per kg protein), and higher values were reported for beef (45 - 640 kg CO_2 per kg protein) and lamb (51 - 750 kg CO_2 kg protein). Moreover, it is worth to notice that the 77% of the catches of the Northern Adriatic Sea consisted of small pelagic fishes, which had the lowest carbon footprint (2.1 kg CO_2 per kg of proteins).

3.5. Conclusions

This work highlighted the high levels of CO_2 emitted in the Northern and Central Adriatic Sea by the trawler fleet (LOA >15m), as well as the different efficiency level of the fishing gears and the emissions intensity for the main landing groups. Even if there are some limitations, such as the lack of data about smaller trawlers or the possible inaccuracy of the fuel estimation, these results could be useful for policy makers to implement the current fishery managements by considering also emission related problems. Moreover, the outcomes of this work could support researches working on the reduction of the fuel consumption and the CO_2 emissions, but also to get more awareness in the customers for a more conscious choice of the fishery products (*i.e.*, carbon footprint of the species and related to the fishing techniques, preference of local products). Nevertheless, for a more accurate view of the real situation in the Northern and Central Adriatic Sea, this emission inventory should be implemented with data from other fishing segments.

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Appendix III

Supplementary Tables

Table S3.1. Technical characteristics (LOA, GT, Power), speed (F-Speed and N-Speed) and Fuel Consumption (FC) of 9 fishing vessels (2 OTBs, 4 PTMs and 3 RAPs) reported in literature (L-FC) during the fishing (F) and navigation (N) phases, and FC recalculated (R-FC) using the Equation 1.

				Fishing			*Navigation*			
	LOA	**GT**	**Power**	**Speed**	**L-FC**	**R-FC**	**Speed**	**L-FC**	**R-FC**	
Gear	*m*	*ton*	*kW*	*knot*	*l/h*	*l/h*	*knot*	*l/h*	*l/h*	***References***
OTB1	21.5	82	478	3.8	60 ± 3	75	10	54.1	59.9	*Buglioni et al. 2011*
OTB2	22.8	91	574	3.8	64 ± 5	90	10	55.4	71.9	*Buglioni et al. 2011*
PTM1	27	104.1	809	4.4	129 ± 9	127	10	85 ± 19	101.4	*Sala et al. 2011*
PTM2	28.95	117.7	940	4.4	133 ± 8	147	10	101 ± 25	117.8	*Sala et al. 2011*
PTM3	28.6	99	940	4.3	104 ± 8	147	10	94	117.8	*Buglioni et al. 2011*
PTM4	28.95	138	940	4.4	126 ± 3	147	10	84.5	117.8	*Buglioni et al. 2011*
RAP1	40.11	417	1467	6.4	476	230	-	-	183.9	*Marlen et al. 2014*
RAP2	42.35	494	1470	5	176	230	-	-	184.2	*Marlen et al. 2014*
RAP3	41.15	438	1471	5	233	230	-	-	184.4	*Marlen et al. 2014*

Table S3.2. Length, hours, total fuel, fuel per vessel, fuel per vessel per day estimated in 2015 and 2016.

			FISHING								
2016	**Length**	**Time**	**Fuel**	**Fuel/v**	**Fuel/v/d**	2016	**Length**	**Time**	**Fuel**	**Fuel/v**	**Fuel/v/d**
	km (1000)	*h (1000)*	*l (1000)*	*l (1000)*	*l*		*km (1000)*	*h (1000)*	*l (1000)*	*l (1000)*	*l*
LOTB	2962	471	21918	70	426		3081	487	22875	77	468
SOTB	926	157	3934	27	167		1027	173	4269	28	169
RAP	1113	108	6109	89	537		1144	109	6275	90	543
PTM	445	61	3730	40	241		479	66	3886	40	240
ALL	**5447**	**797**	**35691**	**58**	**350**		**5732**	**835**	**37304**	**60**	**366**
			NAVIGATION								
	Length	**Time**	**Fuel**	**Fuel/v**	**Fuel/v/d**		**Length**	**Time**	**Fuel**	**Fuel/v**	**Fuel/v/d**
	km (1000)	*h (1000)*	*l (1000)*	*l (1000)*	*l*		*km (1000)*	*h (1000)*	*l (1000)*	*l (1000)*	*l*
LOTB	1656	280	10744	34	209		1705	288	11030	37	226
SOTB	543	215	4837	34	205		570	231	5418	35	215
RAP	544	94	4195	61	368		605	92	4094	58	354
PTM	1191	154	7634	81	492		1170	147	7574	77	468
ALL	**3934**	**743**	**27410**	**44**	**269**		**4050**	**758**	**28116**	**46**	**276**
			FISHING and NAVIGATION								
	Length	**Time**	**Fuel**	**Fuel/v**	**Fuel/v/d**		**Length**	**Time**	**Fuel**	**Fuel/v**	**Fuel/v/d**
	km (1000)	*h (1000)*	*l (1000)*	*l (1000)*	*l*		*km (1000)*	*h (1000)*	*l (1000)*	*l (1000)*	*l*
LOTB	4618	751	32662	105	634		4787	775	33904	114	694
SOTB	1469	373	8771	61	372		1597	405	9687	63	384
RAP	1656	201	10304	149	905		1749	201	10369	148	898
PTM	1637	215	11365	121	733		1649	213	11460	117	709
ALL	**9381**	**1540**	**63101**	**102**	**619**		**9782**	**1594**	**65420**	**106**	**643**

Table S3.3. Emission intensity disaggregated among species groups and fishing gears

	SOTB			**LOTB**			**RAP**			**PTM**		
	CO_2/kg	**Landing**	**CO_2**	**CO_2/kg**	**Landing**	**CO_2**	**CO_2/kg**	**Landing**	**CO_2**	**CO_2/kg**	**Landing**	**CO_2**
	kg/kg	*tonnes*	*tonnes*	*kg/kg*	*tonnes*	*tonnes*	*kg/kg*	*tonnes*	*tonnes*	*kg/kg*	*tonnes*	*tonnes*
CPH	7.21	56.5	407	14.54	266	3868	9.67	355	3433	11.43	29	331
MLS	-	0	0	13.41	2	27	9.01	224	2018	-	0	0
S-PF	7.12	3	21	14.07	4	56	-	0	0	0.41	6527	2611
B-PF	6.91	1	7	11.41	6	68	-	0	0	0.32	6	2
DF	6.99	35.5	248	13.83	207	2863	11.24	62	697	1.15	121	139
FF	7.12	4	28	10.78	26	280	10.39	464	4821	15.37	10	154
CRS	7.01	5	35	15.49	28	434	10.21	79	807	13.99	4	56

Overall Conclusions

The primary aim of this research was to further improve the knowledge about the fishing activities in one of the most exploited basins of the entire Mediterranean Sea, where different countries share the fisheries resources, the Northern and Central Adriatic Sea. Since the trawling activities have been recognised as one of the more harmful fishing techniques, causing structural modifications of marine communities and habitat alterations, this research was focused on this fleet, and in particular on Small and Large bottom otter trawl (LOA under and over 18 m, respectively), *Rapido* trawl, a sort of beam trawl, and Midwater Pair Trawl.

The three objectives developed in this research can be considered complementary to each other and have allowed to reach a more accurate evaluation of the fishing activities in the Northern and Central Adriatic Sea.

Overall, the whole GSA17 was assessed in term of fishing effort and CO_2 emissions, by considering the Italian, Croatian and Slovenian trawling fleet with a LOA over 15 m, while in a smaller area, located in the northernmost part of the Adriatic Sea, the fishing effort relative to the Chioggia fleet was associate with landing and economic value data. The latter point resulted very useful to understand the fishermen behaviour, the efficiency of the gears, and partially better explain the results relative to the fishing effort and emissions. The utilization of AIS data, whose importance has been increasingly recognised by the scientific communities, played a key role in the whole research, allowing a very accurate spatio and temporal analysis of the fishing activities.

The most exploited areas of the GSA17, as well as the site of CO_2 emissions, have been assessed highlighting the presence of different fishing grounds exploited by different trawling gears, and the high level of fishing pressure, highlighted in previous studies (AdriaMed, 2004; Barausse et al., 2009; Pranovi et al., 2015; Fortibuoni et al., 2017), has been confirmed. Indeed, about 87% of the area was interested by fishing activities and about 45% of the area was exploited with a very high level of fishing effort (> 100%). Consequently, the contribute to the CO_2 emissions of the trawl fishing activities has been estimated in about 180 thousand tonnes per year. The fishing effort resulted stable in the investigated years (2015 and 2016), both in term of level and spatial distribution of the fishing grounds, highlighting temporal and spatial patterns of distribution of the fishing activities. In particular, non-random behaviours of the Adriatic trawl fleet, maybe influenced by handed down patterns of fishing performance, regulatory limitations and bathymetric features, as well as the partial overlapping of the fishing grounds of the different fishing gears, were observed. It is worth to notice that since this work was focused only on the trawlers with a LOA over 15 m, a considerable portion of the GSA17 was not considered and therefore the real level of exploitation of the GSA17 was higher. This is very alarming because, by continuing with this level of exploitation and without diversify the areas interested by the fishing activities, the fish stocks are destined to collapse.

Regarding the three countries involved, the Italian side resulted the most exploited, while low fishing effort was recorded in Croatia, excluding the southernmost part, and in Slovenia. The notably difference among these countries was due to the size of the Italian trawl fleet, accounting about 90% of the trawlers with a LOA over 15m.

The analyses performed by disaggregating the fishing gears showed clear differences among the four fishing segments, in term of fishing grounds, level of fishing effort, intensity of emissions, catches efficiency and economic value. Specifically, the main contribution to the total fishing effort was due to the LOTB (> 50%), which showed the widest exploited area, as well as the major number of fishing vessels (about 300 units). Moreover, this fishing segment was responsible also for the 50% of the whole CO_2 emissions, and highest emission intensity (14 kg CO_2 per kg of landing). However, the total landing of this fleet was relative lower compared to RAP and PTM. The fishing effort produced by RAP, a specific Italian gear targeting mainly flatfish and scallops (Pranovi et al., 2015), accounted for about 20% of the total one, but since it was concentrated in smaller fishing grounds it caused a heavy exploitation of the coastal zone. Moreover, the standardization of the fishing effort per number of vessels, highlighted even more the high level of fishing effort caused by RAP. Similarly, the CO_2 emission per vessel resulted higher for RAP, and presumably this was due to the intense activity of this fishing segment and its higher engine power. Moreover, medium-high value of emission intensity was recorded (about 10 kg CO_2 per kg of landing). However, due to the high commercial value of the target species (*e.g.*, common sole and queen scallops; ISMEA[12]), the ratio between economic value and landing results the most profitable among the fishing segments. The SOTB showed a modest fishing effort, mainly located along the coastal areas, presenting some exclusive fishing grounds, such as the Gulf of Trieste and the northern part of the Istrian peninsula. Moreover, the fishing activities of SOTB was the only one detected in all the three countries. Even if the quantity of CO_2 produced by the SOTB activities was the lowest among fishing gears, the emission intensity was medium-low (about 6 kg CO_2 to kg of landing). The PTM, a midwater trawler targeting small pelagic species, which are the main resources of this basin (Carpi et al., 2017), showed a peculiar fishing behaviour, directly dependent on the

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[12] http://www.ismea.it/istituto-di-servizi-per-il-mercato-agricolo-alimentare

presence of school fish, identified with echosounder and sonar. Therefore, the fishing ground resulted widespread and the fishing effort lower compared to the others fishing segments. Due to its fishing behaviour, the CO_2 emissions were mainly recorded during the navigation phases, differently to the other gears where the emissions were mainly related to the fishing phase. Even if the total emissions were comparable to the ones of the RAP, PTM was the most efficient fishing gears, showing the highest quantity of landing, and therefore very low emission intensity (0.5 kg CO_2 per kg of landing). However, differently to the other gears targeting species with high commercial values, PTM caught mainly small pelagic fishes, and in particular sardines and anchovies, which have a very low market price (ISMEA). Therefore, in order to ensure adequate incomes, PTM needs to catch high quantity of these marine resources. For this reason, specific directives were recently established in order to regulate these important resources which are at the bottom of the food web. Moreover, since the main gear used to catch small pelagic fishes in Croatia and Slovenia is the Purse Seine (Status and conservation of fisheries in the Adriatic, UNEP-MAP-RAC/SPA, 2014), the fishing effort of the PTM was not recorded in these countries.

The seasonal pattern of distribution resulted similar for all the fishing segments, and in particular regardless from the fishing gears the fishing activities were mainly concentrated in autumn and spring. Presumably, the high fishing effort recorded in autumn could be a consequence of the summer Italian biological recovery period, and for both the seasons the weather conditions and the spatial distribution of the target species played a key role. The fishing catches distribution, even if carried out in a smaller area, highlighted the wide presence in autumn and spring of species with high commercial values (*e.g.*, common sole, cuttlefish, musky octopus), but also very high density of small pelagic species. The high-resolution maps of distribution of the main target species caught in the Northern Adriatic Sea resulted in accordance with previous studies carried out through data collected during scientific surveys (*e.g.*, Piccinetti et al., 2012; Grati et al., 2013; Scarcella et al., 2014), confirming the validity of the method used to associate the landing with the fishing effort. Moreover, these results allowed to better understand the seasonal fishermen behaviour.

The exploration of different peculiar case studies showed the application opportunities within a context of fishery management and monitoring. Indeed, these results could be useful within the context of the implementation of new fisheries management strategies in the GSA17 and also at fishing gear level. In particular, in the Pomo Pit, taking advantage from the spatial distribution of the fishing effort, it was possible to assess the side effects due to the temporary closure of the Pomo Pit area, with a significant increase of the fishing effort in the zone around the protected area. However, it is worth noting that this increase accounted for a small amount of the effort missed with the closure (less than 50%), suggesting a complete change of the fishing strategies adopted by a consistent portion of the trawling fleet operating in that area.

Regarding the case study concerning a hypothetical ban for trawling activities within 6-nm from the Italian coast, the analyses have highlighted an intensive exploitation of this area, especially by RAP and SOTB fleets. In fact, the target species of the RAP are mainly located in the coastal area (Pranovi et al., 2015), and the SOTB, due to their small dimensions, avoid operating in areas too far from the coast. Therefore, in case of an implementation of the 3-nm ban, these two fleet segments would be the most negatively affected by the ban. All this confirmed that the closure of the 6nm-area would reduce the fishing grounds for trawlers. Nevertheless, as highlighted for the Pomo Pit area, in the prospective of future enforcement of the directive a possible spill-over effect should be considered in order to avoid an increase of the pre-existent fishing effort.

The so-called Sole Sanctuary, localized in the middle of Northern Adriatic Sea and recognised as a persistent sole spawning area (Scarcella et al., 2014), resulted moderately exploited. According to previous studies (Grati et al., 2013; Scarcella et al., 2014; Bastardie et al., 2017; Santelli et al., 2017), the low level of exploitation can be related on one side to the high concentration of bryozoans (*e.g.*, *Amathia semiconvoluta*; Salvalaggio et al., 2014), which makes the seabed untrawlable for the risk to obstruct the nets, and on the other side to the high presence of holothurians (*e.g.*, *Holothuria forskali* and *Parastichopus regalis*), characterized by the capacity to eviscerate their internal organs under stress conditions, which makes the fishery resources less saleable (Bastardie et al., 2017). Even if this area was partially reallocated in the recent years and the new Sole Sanctuary was smaller than the old one, the fishing effort recorded in the two sites resulted quite similar. However, catches and economic value recorded in the previous site resulted higher than the ones of the new site. Moreover, the ratio between economic value and landing highlighted the presence in the previous site of species with higher commercial value.

Recently, a Site of Community Importance was established in the area near the Po River outlet in order to protect dolphins and turtles. The analyses performed in this area highlighted the presence of species with high commercial values (such as common sole). Moreover, high value of economic value per km^2 were recorded.

Previous published works have already investigated the fishing activities in the Adriatic Sea considering different aspects, such as spatial distribution of the nominal fishing effort, species distribution, population analyses, and landing time series analysis (*e.g.,* Scarcella et al., 2014;

Pranovi et al., 2015; Fortibuoni et al., 2017; Carpi et al., 2017; Russo et al., 2019). However, the integrated and interdisciplinary approach here applied to assess the fishing effort, estimated as swept area, in association with landings, economic value and CO_2 emissions, disaggregating also per fishing gears and seasons, has never been performed in the Adriatic Sea.

Despite the enforcement of different EU directives established to guarantee a sustainable level of fishing exploitation (CFP, MSFD and MSP), in Mediterranean Sea their application resulted very challenging due to the complexity of the ecological, economic, social and political differences within this basin (Carpi et al., 2017; Libralato et al., 2018). To date, in areas with sharing resources and high level of exploitation, the development of an effective fishery management plan is more and more needed in order to reduce the over-exploitation of the marine resources ensuring their availability for the future generations (Bastardie et al., 2017). This will be in line with the 2030 Agenda for Sustainable Development, which established 17 Sustainable Development Goals (SDGs), and in particular with SDG 14 “Conserve and sustainably use the oceans, seas and marine resources for sustainable development”. In this context, this research provided new insights for a sustainable fisheries management, making available useful information for the monitoring and the assessment of the trawl fishing activities in a focal area of the Mediterranean Sea.

References of Introduction and Conclusions

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