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Towards an understanding of trawling impacts on Blanes and Palamós submarine canyons. Costa Brava, Spain.

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"There, where I have passed, the grass will never grow again."

Attila the Hun

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Abstract

The continuous overexploitation of marine resources has triggered a progressive expansion of fishing fleets to deeper waters, threatening marine communities and ecosystems. The present study conforms to a detailed analysis of deep bottom trawling surrounding Blanes and Palamós submarine canyons, in the Northwestern Mediterranean Sea. The main idea was to assess the spatiotemporal evolution of the fishing grounds encompassing these canyons, as well as to identify the effects of bottom trawling on the seafloor's geomorphology and megabenthic assemblages. Vessel Monitoring System (VMS) and Automatic Identification System (AIS) data were used to quantify the pressure exerted by bottom trawling on the study area during the past decade (2008-2019), whereas video footage from a Remotely Operated Vehicle (ROV) was used to determine the geomorphological and ecological state of the seafloor, using trawl marks as an indicator of the physical damage of bottom trawling. The results showed that AIS data was an unreliable mechanism to assess fishing effort in bottom trawling grounds surrounding Blanes Canyon. Spatiotemporal evolution of VMS data indicated a growth of fishing areas and fishing effort during the last decade. Furthermore, fishing grounds were highly impacted, with several trawl marks and reduced abundance of megabenthic communities, especially of vulnerable sessile organisms with reduced mobility. In view of the global dimension that this fishing technique encompasses, an integrated management is needed to guarantee a sustainable deep-sea fishery and promote the protection and recovery of deep-sea marine communities.

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1. Introduction

Huxley, in the year 1883, postulated: *"Probably all the great sea fisheries are inexhaustible; that is to say, that nothing we do seriously affects the numbers of fish. Any attempt to regulate these fisheries seems consequently, from the nature of the case, to be useless"*. At that time, it was presumed from the vastness of the ocean that fishing would not drive species to extinction. However, this conviction was disproved at the beginning of the 20th century (Jackson, 2001). Global trends in the world's marine fish stocks made by the Food and Agriculture Organization today (Food and Agriculture Organization, 2018) show that the percentage of overfishing is growing year by year. This makes ecosystems more susceptible to other natural and human disturbances, such as nutrient loading, disease, storms, and climate change (Jackson, 2001). As Roberts claimed, "*we are losing species far more quickly than we can describe them"* (Roberts, 2002). Hence, there is an urgent need to properly protect the ocean as well as base future management[1] decisions on the precautionary principle and strong scientific knowledge (Baker et al., 2009).

Bottom trawling consists in hauling a net that is supported by two boards, also called doors (Palanques et al., 2006; Martín et al., 2014a; *Fig. 1.1*). This fishing technique is considered one of the most damaging fishing activities because of its indiscriminate catch and, consequently, the large number of unwanted species discards (Kelleher, 2005). It is worth noticing that the Mediterranean-wide estimate of discards of the deep-water trawl fishery for shrimps is 39.2% of the total catch (Kelleher, 2005). However, the impacts of bottom trawling are not only limited to the ecological impacts related to stock overexploitation and high discards, but also to the seabed since the gear can cause considerable damage to the sedimentary environment and to benthic communities inhabiting on the seafloor (Martin et al., 2014b).

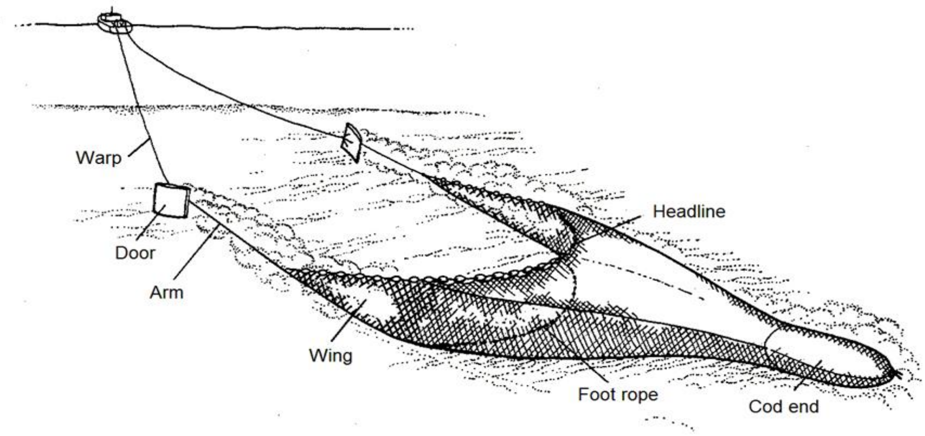

Figure 1.1. Schematic representation of a typical bottom trawler (Palanques et al., 2001).

1.1. Historical context of trawling

Bottom trawling has been practiced since the XIV Century (Sahrhage and Lundbeck, 1992). During the XIX Century, with the arrival of the Industrial Revolution and the introduction of the steam engine, fishing vessels were able to expand to farther areas and capture substantial quantities of fish. Due to the continuous exploitation of sea resources in shallow waters, fishing fleets have been expanding to deeper waters to capture a greater number of catches since the 1950s (Watson and Morato, 2013). Deep trawling occurs near

[1] Fisheries Management is defined here as *"the process that creates rules that are needed to prevent overfishing and help overfished stocks rebound"*. (Wilson and McCay, 2001).

morphologies that favor the aggregation of many species, such as submarine canyons and seamounts (Fernandez-Arcaya et al., 2017; Clark and Koslow, 2007). In the 1980s, significant alterations to ecosystems were already evident, and there was a drop of global catches due to the decline of shallow stocks (Callaway et al., 2007). This encouraged the development of larger vessels, more powerful winches, stronger cables and heavier gear, which contributed to expand fishing efforts substantially (Roberts, 2002). Improved fishing technologies, together with the exponential growth of the human population and its food demand, has prompted trawl fisheries to increase and expand to deeper and unexplored areas over the last decades with little regulation (Pauly et al., 2003; Morato et al., 2006; Martín et al., 2014b).

Deep-sea fish are considered to be highly vulnerable and potentially have little resilience to overexploitation because of their late maturation, low fecundity, slow growth rates, and long lifespans (Baker et al., 2009; Koslow et al., 2000), which explains the rapid stock declines and slow stock recovery (Devine et al., 2006). The expansion of fisheries towards greater depths and the improvements in fishing technology in the attempt to increase their productive capacity questions the sustainability in the exploitation of deep-sea species. Today, most deep-water stocks are overfished or even depleted, which may have ecological implications over the long term (Koslow et al., 2000; Roberts, 2002).

The characteristics of deep-sea species highlighted above compel us to rethink attitudes on exploitation and also realize that deep-water fisheries could repeat the process of stock depletion of shallow-water fisheries, which has been its hallmark. However, in deep-sea species, depletion is more rapid, and recovery slower and less certain than in shallow water (Roberts, 2002). Thus, deep-water habitats should be contemplated as the new candidates for conservation, instead of the replacement for declining shallow-water fisheries. In this way, there is the growing urgency to properly monitor deep-sea fisheries, so that the distribution of fishing activity can be tracked and studied to correctly manage their impacts on the marine environment (Shepperson et al., 2017).

1.2. Impacts of bottom trawling

The persistent and uninterrupted dragging of bottom trawling gear on the seafloor causes a general degradation of marine ecosystems in multiple ways, as it affects both the physical environment and the living organisms. The key impacts considered relevant for this research will be exposed briefly as follows. The majority of studies focus on shallow waters (<200 m depth), whereas deep environments (>200 m depth (Thistle, 2003)) are less studied. However, ecological impacts on deep-sea communities are, broadly speaking, amplifications of the impacts observed in shallow ecosystems (Gage et al., 2005; Clark & Koslow, 2007).

1.2.1. Seabed morphology

The different disturbances on the seabed depend on sediment composition, topography, trawling speed, and weight of trawling equipment, as the gear is physically pressing the seafloor (Gray and Elliott, 2009; O'Neill and Ivanovic´, 2016). Although these impacts affect continental shelf and deep-sea waters in a similar way, it is worth noticing that the incidence on ecosystems is more severe and long-lasting with increasing depth owing to fewer sediment resuspension mechanisms and lower sediment fluxes of the deeper environments (Martin et al., 2014a). Herein lies the essence of this study.

Persistent furrows and marks, along with the removal of upper sediment layers, are some of the most evident geomorphological consequences of towing fishing gear along the seabed. Buhl-Mortensen et al. (2013) stated the significance of the vertical penetration of trawling gear on seafloor sediments, which can reach several centimeters for the net and up to 30 cm for the doors. In deeper slope environments, Paradis et al. (2019) demonstrated various trawl marks that reached hundreds of meters long and were 70 cm deep, which evidences the greater penetration of trawl doors on the seafloor in comparison to shallow shelf environments, associated to the heavier gear required to successfully obtain resources in deeper environments (Martin et al., 2014a; Clark et al., 2016). Marks on inshore sediments can persist up to a few months on coarse substrates (Lokkeborg and Fossa, 2011) and until 2 years in muddy areas (Ball et al., 2000). Deep marine environments have weaker physical processes than shallower environments, which result in long-lasting geomorphological impacts. Clark et al. (2010) reported visible furrows in deep-sea New Zealand waters on soft sediments 5 years after fishing ceased.

Continuous deep-sea bottom trawling smoothens the seafloor, leaving behind eroded seafloor with altered sediment characteristics (Martin et al., 2014b; Puig et al., 2012). The continuous disturbance of the seafloor caused by bottom trawlers also modifies the physical properties of sediments, mainly as a result of the resuspension of large volumes of sediment and compaction of the seafloor. Sediment dry bulk density in trawled sites tend to be greater due to the pressure exerted by the fishing gear (Martín et al., 2014b). Moreover, the continuous sediment resuspension promotes the sorting of particles based on their settling speed, causing finer particles to be preferentially reallocated than the coarser ones, promoting a general grain-size coarsening of the seafloor (Martín et al., 2014b). Sediment resuspended by bottom trawling can be transported great distances from fishing grounds, provoking a wider extension of the impacts beyond fishing grounds. This sediment distribution may deplete some sites from fresh sediment and generate depocenters further away (Martín et al., 2014a; Palanques et al., 2014; Paradis, 2017).

Many studies show variations in available carbon in both shallow and deep trawling grounds (Palanques et al., 2006; Pusceddu et al., 2014; Martín et al., 2014b; Paradis et al., 2019; Tiano et al., 2019). Tiano et al. (2019), reported reductions of labile organic matter (in the form of chlorophyll *a*) and organic carbon in shallow waters after a trawling event. However, the levels were rapidly recovered, a fact that was attributed to the temporal removal of demersal organisms. The stirring of sediment at deeper waters releases the stored carbon into the water column, depleting the surface of labile organic matter and organic carbon (Pusceddu et al., 2014; Martín et al., 2014b) and altering its cycle. Nevertheless, the lower resilience of deep-sea environments may leave these parameters in their depleted state for longer periods (Clark et al., 2016), making the area's ecosystem more dependent on the arrival of fresh organic matter (Paradis et al., 2019).

Trawling activities have also modified nutrient cycling in sediments. Tiano et al. (2019) noted a reduction of ammonium fluxes from the sediment to the overlying water in shallow environments, which can be enhanced in deeper fishing grounds. Indeed, organic carbon turnover rates are substantially lower in deeper continental slopes (Pusceddu et al., 2014). The biogeochemical cycles are a form of balance comprising chemical reactions, metabolic transformations and abiotic conditions, and the alteration of any of the components may have impacts on the ecosystem. Reductions in water column oxygen concentration and increases in the degree of sediment oxygenation have also been reported (Tiano et al., 2019). This can considerably change microbial ecosystems as well as play an essential role in the remineralization of organic matter (Duplisea et al., 2001; Tiano et al, 2019). In response to alterations in carbon mineralisation and nutrient cycling, modifications on the global biogeochemical processes on the seafloor might be expected (Ferguson et al., 2020).

As previously mentioned, these disturbances tend to be less durable when referring to shallow waters, since submarine landscapes in these areas present greater natural dynamization that can also resuspend large volumes of sediment (Dyekjaer et al., 1995; Duplisea et al., 2001; Ferré et al., 2008). Conversely, alterations caused by trawling gear are likely to be more persistent in deeper waters and areas farther from the coastline, where the seafloor is rarely affected by natural disturbances such as storms (Kaiser, 1998; Collie et al., 2000; Duplisea et al., 2001). It is worth noting the correlation between these statements and the tendency of fishing fleets to move towards deeper areas, as this displacement may cause a severe impact on the associated ecosystems.

1.2.2. Ecosystem and communities

Repeated trawling affects the ecology of local marine communities broadly, considering that it can produce biological and physicochemical variations (Thrush and Dayton, 2002). In such a way, communities can be damaged directly (e.g., decline in the number of individuals of a population through removal or extermination by trawling gear) and indirectly (e.g., by altering the available nutrients and affecting the ecosystem's metabolic function). Moreover, due to the poor range of selectivity of this fishing technique, non-targeted species (bycatch) are commonly captured and involuntarily exterminated, which may attract scavengers or predators to fishing grounds, producing variabilities in the community composition (Hinz et al., 2009).

Communities are highly sensitive to variations. Hence, a minor disequilibrium in the population size can imbalance the entire trophic chain. The magnitude of the ecosystem response to trawling disturbance (the resilience of an ecosystem) depends on the number and identity of the species present in the area, their biological traits, and ecological functions (De Juan et al., 2007). It is also important to consider the degree of endemism or fragility of affected species (Martín et al., 2014a). The required trawling effort to provoke a certain magnitude of damage in deep waters has still yet to be well researched. Nevertheless, several empirical data studies focused on shallow systems' trawling can serve as an approximation to realise the possible impacts on the deep-sea and the response that different phyla could have (Clark et al., 2016).

Demersal species are known to be more affected by trawling disturbances. Some of them have the ability to overcome perturbations due to the adaptation of their life strategies. However, a large number of invertebrates possess an extremely slow recovery capacity, making them highly sensitive to trawling impacts (Clark et al., 2016). Species can cope with certain pressures to different extents. Benthic assemblages, including corals, sponges, bryozoans, and other sessile animal forms, are known to be the most directly affected organisms due to their three-dimensional structure. Still, indirect impacts such as sediment plumes also suffocate these infaunal species (Clark et al., 2016). Thus, water turbidity caused by sediment resuspension affects suspension feeders directly, e.g. bivalves, sponges, and corals (Jones, 1992) and photosynthetic organisms, e.g. microorganisms, such as phytoplankton, and macroorganisms, including seagrasses or seaweeds (Caddy, 2000). These organisms are paramount components of marine communities, and their removal or death can alter the ecosystem structure.

Macrobenthic species play an important role in benthic communities. Bioturbating and burrowing species can actively collaborate with the remineralization of organic matter, as they facilitate oxygen inputs to different depths (Krantzberg, 1985). However, changes in sediment physical properties on marine shelves are known to dislodge local epifauna, whereas the alterations in the geomorphology can make the area inappropriate for settlement (Kaiser et al., 2000). Therefore, the loss of an ecosystem's bioturbators can significantly alter the benthic community composition and structure (Kaiser et al., 2000), which could have profound impacts on sediment biogeochemistry (Duplisea et al., 2001).

In deep-sea bottom trawling grounds of the Mediterranean Sea, Pusceddu et al. (2014) demonstrated a diminishment in meiofauna abundance as well as a definite impact on the biodiversity and richness of nematode species. Besides, modifications to the biological traits of nematode assemblages were noticed to vary depending on the trawled state and the depth. These assemblages held a significant portion of opportunistic species (r strategists) in trawled sites and tended to be occupied by meiofauna of higher individual biomass (typical from deeper grounds), indicating a shift in the meiofauna composition of deep trawling grounds. As has been previously highlighted, deep-sea megabenthic organisms are considered to be particularly vulnerable as a result of the ecological strategies of conservation (e.g. low fecundity and metabolic rates) required to inhabit deep-sea regions (Sardà et al., 2009).

Moreover, the physical and geomorphologic alterations caused by trawling gear (i.e. removal of heterogeneous seafloor morphologies and smoothening of the seafloor) can severely impair habitats and benthic organisms on the continental margins and slopes, which can lead to reduced biodiversity and changes in the community composition (Jackson, 2001; Kaiser et al., 2002). However, more research in the field is needed to accurately assess the impact this fishing activity entails in a deep environment, since the exact consequences have yet to be fully understood. The uncertain and unpredictable effects of these impacts give a high complexity and concern to the topic.

1.3. Regulation and monitoring systems in the Mediterranean

Fishing activities represent a considerable agent in the economy of every coastal country. However, fishing tends to overexploit the resource and inevitably cause substantial impacts in the ecosystem, as explained above. Consequently, regulation in this field needs to be both strict and understandable.

Mediterranean fisheries are governed under the EU management regulation, using an ecosystem approach of fisheries management to ensure the maximum ecosystem stability (European Maritime and Fisheries Fund, n.d.). The primary directive that legislates in this area is the Council Regulation (EC) No. 1967/2006, also known as “Mediterranean Regulation” which controls a wide range of aspects. The most relevant in terms of trawling is the restriction of the minimum mesh size for towed nets to 40 mm -article 9- and the prohibition of trawl nets at depths below 50 m and beyond 1.000 m -article 4 and 13- (Council of the European Union, 2006).

The most common way to ensure the accurate monitoring of this regulation is by controlling vessel positioning. The EU was the first to introduce in 2011 a mandatory monitoring system for vessels above 12 m length belonging to the EU Member States in its regulation. This system, called Vessel Monitoring System (VMS), is a satellite-tracking device in which a vessel cannot leave a port without (European Commission Regulation, 2009).

VMS are programmed to transmit data about the vessel identification, the geographical position (latitude and longitude), the date and time, and the speed and course of the vessel to the fisheries authorities at regular intervals. The data are transmitted every 10 minutes but are available for research and scientific purposes in longer intervals of 2 hours (European Commission Regulation, 2009). However, the low frequency of VMS data available for research complicates the reconstruction of fishing effort (Lambert et al., 2012).

The VMS technology is based on three pillars: the shipboard equipment, the communications systems, and the fishery monitoring center (*Fig. 1.2*). Firstly, shipboard equipment, which consists of an antenna and transceiver, an external power source, and some cabling, transmits the information to the fishery monitoring center. A communication system manages this transmission. There are multiple types of services used for this purpose. The most known are Argos (polar-orbiting satellites from USA’s National Oceanic and Atmospheric Administration), and Inmarsat-C and D+ (geostationary satellites along the equator) used by the vast majority of European vessels. Finally, the information is compiled in the fishery monitoring center. These centers are specially controlled, as the information collected has a high value. Besides compiling all the data sent, a crucial task executed in these centers is to compare the location and identity of VMS units with territorial boundaries, protected areas, and other critical geographic points. If some irregularity is detected, there is an alarm system incorporated that alerts local authorities (Food and Agriculture Organization, 2010-2020).

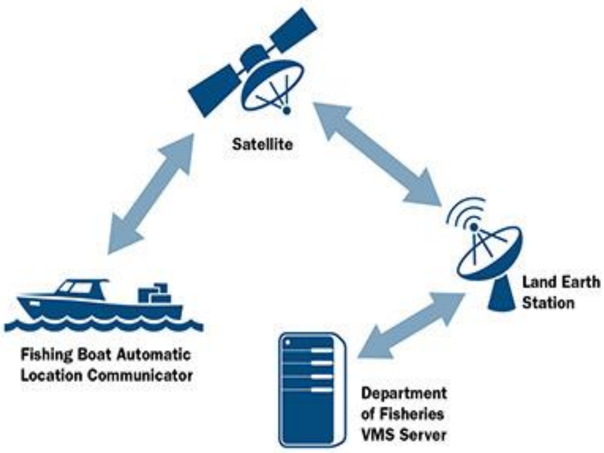

Figure 1.2. Explanation of the VMS tracking system (Department of Primary Industries and Regional Development, 2014).

In addition to VMS, there is another geopositioning monitoring system established, called AIS (Automatic Identification System), which transmits data at shorter intervals, every few seconds or minutes. AIS not only transmits information to a monitoring center -as VMS-, but also transmits information between vessels until it arrives at a land station (Shepperson et al., 2017). This system was initially put in place to avoid ship collisions. AIS data consists of position, time, speed, and course (Maritime Safety Committee, 1998). Nevertheless, this system presents some failures. The fact that the transmission depends on the vessel spreading can cause the loss of a transmission in a low or high vessel density area, promoting several gaps in the spatial coverage (Kroodsma et al., 2018). Moreover, vessels can turn off AIS transmission, further increasing the number of gaps (Shepperson et al., 2017); this is a common practice of fishing vessels when exploring new fishing grounds.

International Convention for the Safety of Life at Sea (SOLAS), which establishes minimum standards to ensure safety in vessels, sets out in chapter 5, regulation 19, that "*All ships of 300 gross tonnage and upwards engaged on international voyages and cargo ships of 500 gross tonnage and upwards not engaged on international voyages and passenger ships*" need to carry an AIS system (International Convention for the Safety of Life at Sea, 2002). According to this international regulation, European Commission established in Regulation No. 1224/2009 that "*all vessels exceeding 15 m length overall shall be fitted with and maintained in operation an AIS*" (2009).

To sum up, AIS and VMS present many differences. AIS is mandatory for vessels above 15 m length, its data is partially open to the public, and the transmission frequency is over a few seconds or minutes. Meanwhile, VMS is mandatory for vessels above 12 m length, its data is strictly confidential, only available for scientific purposes, and the poll frequency is 2 hours. The comparison of both positioning systems when assessing fishing effort can provide very different results (Shepperson et al., 2018), and the accuracy of these methods still need to be assessed.

1.4. Trawling in Blanes and Palamós canyons, Catalan margin

1.4.1. Catalan margin

Bottom trawling is one of the most important fishing activities in the western Mediterranean in terms of volume of catches and economic gain. This fishery is characterized by an elevated number of species commercialized in the area (Sanchez et al., 2004), tending to a susceptible overexploitation (Food and Agriculture Organization, 2018).

Along the Catalan coast, demersal marine resources are found on the surroundings of submarine canyons and are mainly caught by bottom trawling. Due to the increase of fishing the Catalan margin has experienced an ongoing decline in catches per unit effort (CPUE) over the past 20 years as a result of growth in trawler engine power and fast technological advances (Sardà et al. 2005).

The deep-sea red shrimp (*Aristeus antennatus)* is one of the most valuable target species of the bottom trawl fishery in the Mediterranean Sea, including the Catalan coast. This species is an essential resource for the local fishermen, although it involves high costs and risks because of its deepwater wildlife -the bathymetric distribution of this species ranges between 100 and 3,000 m depth- (Sardà et al., 2004). Due to the high commercial value of the product, the red shrimp fishery is very lucrative. This species constitutes 3% of total landings, even though it comprises 21% of economic income on an annual average (Tudela et al., 2003; Maynou et al., 2006; Gorelli et al., 2016).

The common trawling gear used along the Catalan margin is the benthic otter trawl *(Fig. 1.1)*. The net is towed across the bottom, and it has a wide mouth (from 40 to 50 m) and a tapered end, which retains the catch. The dimensions of the net range from 80 to 150 m. The two otter boards of the otter trawl gear are heavy (from hundreds of kg to tons, concretely from 400 to 1,200 kg), and the distance between them can be more than 100 m. These are used to maintain the net open and keep it on the seabed (Palanques et al., 2006). The total length of the sweep lines (bridles) that connect the otter boards to the net is from 60 to 200 m long. Different from other bottom towed gears, the otter trawl net does not have the rigid front frame, which allows the gear to adapt to all kinds of terrain. Thus, it can work in an area not accessible to other bottom fishing techniques (Martín et al., 2014a). In terms of the fishing operation, the mean depth of bottom fisheries in the Catalan margin catch is 400-800 m in the sea (Puig et al., 2012).

The Catalan continental extends from the Cap de Creus Canyon (northern limit) to the Ebro River delta (southern limit). The Northwestern Mediterranean margin is characterised by the presence of numerous submarine canyons (*Fig. 1.3*). Along the Catalan margin, trawling is practiced over the heads, rims, and flanks of the many submarine canyons incising the margin (Paradis et al., 2017). According to Harris et al., 2014, submarine canyons are "*steep-walled, sinuous valleys with V-shaped cross sections, axes sloping outward as continuously as river-cut land canyons and relief comparable to even the largest of land canyons"*. These submarine regions can intercept high organic and nutrient inputs, which, combined with heterogeneous morphologies, act as ecological hotspots (De Leo et al., 2010) and nursery areas for many commercial species (Farrugio, 2012).

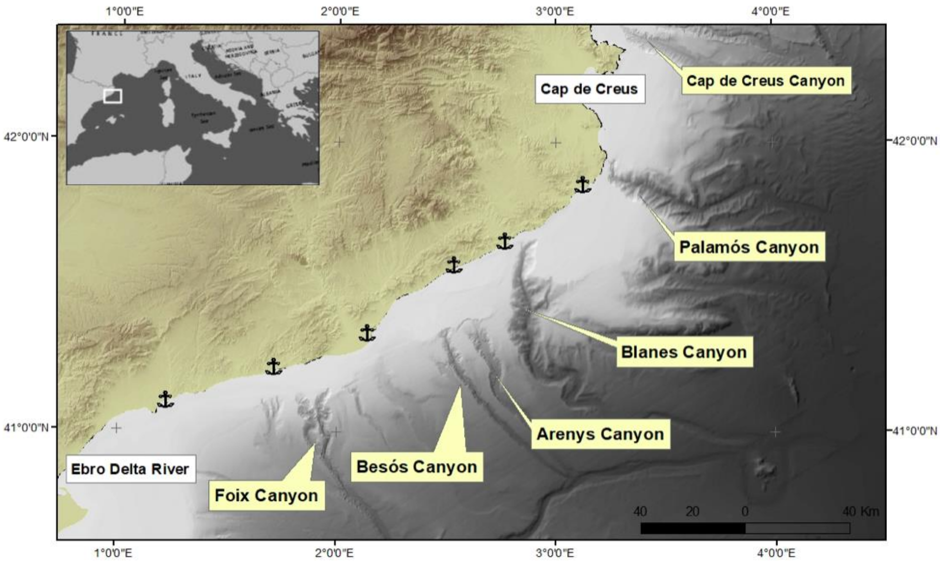

Figure 1.3. Submarine canyons of the Catalan margin. Data acquired from ICGC, Departament de Territori i Sostenibilitat and ICM.

1.4.2. Palamós and Blanes canyons

Blanes and Palamós Canyon (also known as La Fonera) are two of the most prominent canyons of the Catalan coast; consequently, fishing is an important economic activity for these locations (Palanques et al., 2006). Both mentioned canyons incise the continental shelf and receive high sediment inputs from the coastal zone and nearby rivers. Canyons intercept and channelize particles suspended in the water that has been transported by currents in episodes of storms or dense shelf water cascading. Due to the morphology and dynamics of the canyons, bottom trawling is practiced in the vicinities of them (Martin et al., 2006).

As described previously, the red shrimp is one of the targeted species in the Catalan margin. In 2005, a natural oceanographic phenomenon called dense shelf water cascading (DSWC) generated the apparent disappearance of the red shrimp in the fishing areas where it used to inhabit. This event happened due to increased downward current and water turbidity in submarine canyons, which caused the impossibility of organisms to reproduce (Company et al., 2008). Dense shelf water cascading takes place when coastal surface waters become denser than surrounding waters during winter storms. Thus, water cascades downslope and into canyons until reaching its equilibrium density (Canals et al., 2006; Puig et al., 2013). They generate currents reaching depths >500 m, creating a thermohaline and turbidity anomaly in deep waters. Moreover, this phenomenon caused in 2005 shrimp mortality and decreases in the availability of fishing grounds, causing a temporary fishery collapse (Company et al., 2008). However, a relatively fast recovery of landings has been noticed after a few years from DSWC due to the enhanced supply of organic matter that assures an increase of recruitment of shrimp larvae to the fisheries. In fact, two or three years after the cascading event, exceptional catches of small individuals were observed (Gorelli et al., 2016).

As a consequence of this phenomenon, a collaboration between fishermen and scientists started. This collaboration pursued the proper regulation of the fishing activity in the zone to avoid overexploitation and fishing small shrimp individuals during the recruitment period. These actions ended in 2013, when the Development Plan for the red shrimp was approved (Björken et al., 2020). This plan is only implemented in Palamós Canyon, although it is used as a reference for other locations such as Blanes (Björken et al., 2020). The primary objective of the Plan is to regulate the trawling impact when fishing the red shrimp in some areas along the Palamós coast. All the vessels that follow the criteria established by the Plan are local ones that trawl in the regulated areas[2] (*Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente*, 2018).

An update of the plan is exposed in 2018, BOE (State Official Newsletter of Spain). This Development Plan imposes specific limitations on the structure of the fishing net and the maximum amount of time that vessels can fish in the regulated areas (11 hours), as well as a yearly fishing ban of 60 days, besides the national ban usually established between January and March *(Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente, 2020).* Along with these fishing ban periods, there are three trawl ban areas between Palamós and Blanes. One of those, defined by the BOE, is called *Vol de Tossa* (*Ministerio de Agricultura, Alimentación y Medio Ambiente*, 2012). The other two were established in 2018 by Palamós fishing guild to enhance the repopulation of fisheries. These areas are the Repopulation area Blanes-Palamós and the Area of the *Norway lobster* in Roses-Palamós[3] (*Acord de la junta general*, 2018).

The number of trawlers targeting red shrimp in Catalonia has been increasing since the 1950s, reaching a peak in 2006, according to Gorelli et al. (2016)[4]. On account of the red shrimp fishery, Palamós harbour has grown to become one of the main ports of Catalonia, in this day and age. Blanes harbour, located towards the south of Palamós, also supports important bottom trawling fisheries (Gorelli et al., 2016). In Blanes Canyon, the specialised commercial fleet target *A. antennatus* as well (Sardà et al., 2009), having a local fleet fishing between 600 and 800 m depth (Company et al., 2008).

Resulting from the mentioned fishing activity surrounding both canyons, several impacts on the seafloor can be found. Martin et al. (2014) discovered how trawling along the flanks of Palamós Canyon triggers sediment gravity flows, transporting sediments from the fishing grounds to the canyon axis, and increasing sedimentation rates in the canyon's interior, all of which reshape the temporal sedimentary dynamics of the canyon (Martin et al., 2014c; Palanques et al., 2006; Puig et al., 2012, 2015). Bottom trawling also causes erosion and mixing, inducing changes in the grain-size distribution of the remaining sediment (Martin et al., 2014b). Studies concerning Palamós Canyon are considered to be representative of most of the canyons incising the NW Mediterranean continental margin (Canals et al., 2013), which are subjected to a similar intensity of trawling (Puig et al., 2012) such as Blanes Canyon, also considered in this study. In Blanes Canyon, effects of variations in hydrodynamics and particle flux have been attributed to spatiotemporal variations in meiobenthos density and distribution of red shrimp (Sardà et al., 2009). Lopez-Fernandez et al. (2013) observed a higher amount of sediment fluxes in summer possibly due to the fishing activity, followed by a later study proving that sedimentation rates had increased in the canyon's axis (Paradis et al., 2018).

It is fundamental not to forget where we come from and where we are now. As Garrett Hardin wrote in his famous thesis, The Tragedy of the Commons (1968), "*Each man is locked into a system that compels him to increase his herd without limit, in a world that is limited.*" This quote, written years ago, reflects the consequences of this limited world, which gradually come to light in a lot of different fields, including bottom trawling. Thereby, the first step to avoid or mitigate the impacts of this fishing practise is to thoroughly study and investigate the submerged zones. For this reason, it is of crucial importance to track fishing activities, especially in areas where fishing effort is high, so that an efficient and sustainable plan for bottom trawling in the Catalan margin can be accomplished.

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[2] *Annex I* shows a table of the 16 vessels that shall follow the regulation are presented.

[3] *Annex II* represents the three banned areas within the study area.

[4] *Annex I* shows the evolution of the trawling fleet in Blanes and Palamós harbours.

2. Objectives

2.1. General objectives

- Track and study the spatiotemporal distribution of fishing grounds around Blanes and Palamós submarine canyons.
- Identify the impacts of bottom trawling on the seafloor in fishing grounds around Blanes and Palamós submarine canyons.

2.2. Specific objectives

- Compare two types of monitoring systems -VMS and AIS- in 2019.
- Unravel the evolution of fishing grounds and fishing effort in the last decade (2008-2018).
- Identify recurrent, neglected and new fishing areas during that decade.
- Analyse the geomorphologic changes caused by bottom trawling in the canyons.
- Assess the distribution in the abundance of different benthic phyla in Blanes and Palamós canyon flanks, and the effects of bottom trawling.

3. Methodology

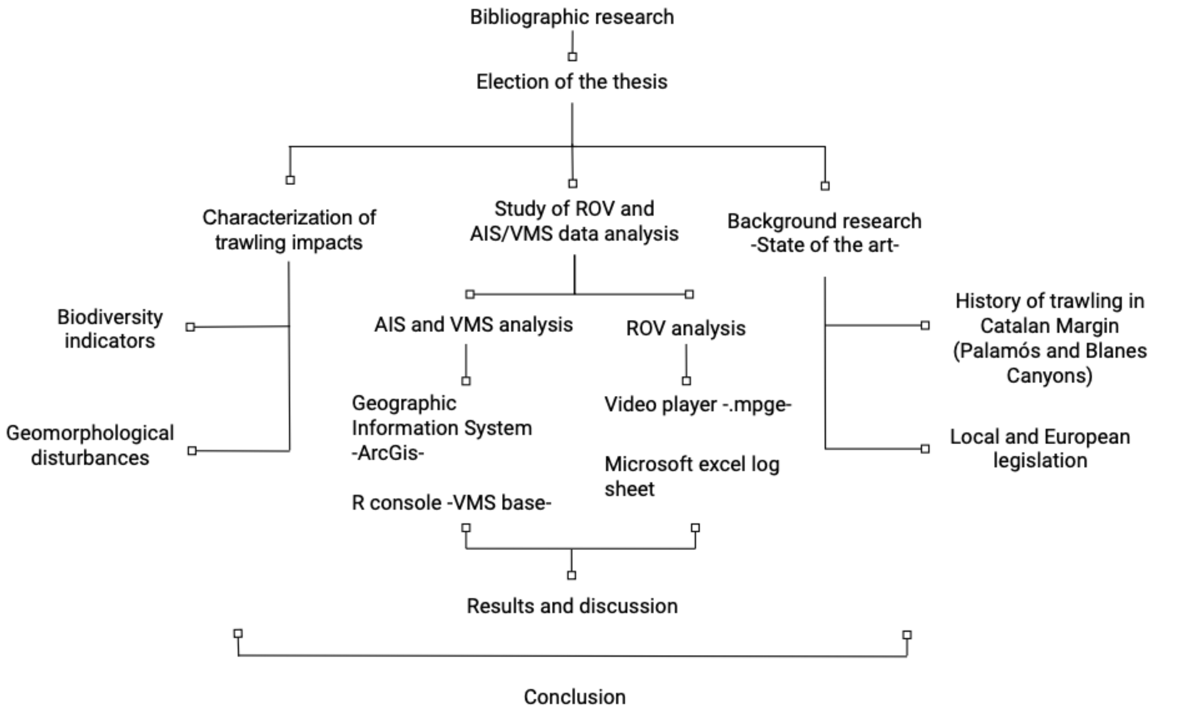

Figure 3.1. Methodological scheme.

3.1. Study area

The present study is focused on Blanes and Palamós canyons, located along the Catalan coast (*Fig. 3.2*). They are two of the largest submarine canyons incising the Catalan margin (Canals et al., 2013).

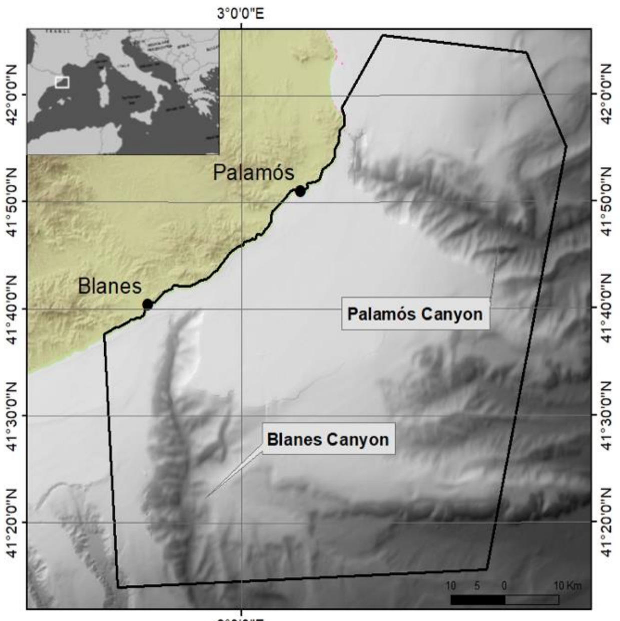

Figure 3.2. Sea bathymetry of the study area. Blanes and Palamós canyons can be clearly distinguished. Data acquired from ICGC and ICM.

Palamós Canyon has a total length of 110 km and a depth range of 60-2,250 m (Canals et al., 2013). It is located less than 1 km from the coastline and 15 km of the canyon incises the continental shelf. Due to its morphology, Palamós Canyon intercepts and channels suspended particles that are transported by currents (Martín et al., 2006). This submarine canyon supports seven fishing grounds[5], with *Sant Sebastià* -on the northern canyon flank- and *Rostoll* -on the southern canyon flank- as the most important ones (Palanques et al., 2006).

Blanes Canyon measures 185 km in length and has a depth range of 70-2,600 m (Canals et al., 2013). It cuts the continental slope in a north-south direction (Zúñiga et al., 2009). The upper canyon is also located close to the coastline, at only 4 km from the shore (Díaz and Maldonado, 1990). The canyon head is linked with the Tordera River, receiving sediment and water contribution from it (Rovira and Batalla, 2006). The width of the canyon increases with depth until it reaches a maximum of 20 km at its deepest part. It presents a V-shaped cross-section in the upper region, indicating high erosion, and a U-shape cross-section in the lower region, representing higher sediment deposition (Canals et al., 1996). This submarine canyon supports eight fishing grounds in its surroundings[6].

3.2. Fishing fleet data, acquisition and processing

Understanding how the fishing fleet has moved in the past decade is fundamental to recognize the impact on the seafloor. Thus, vessel positionings around Palamós and Blanes canyons were collected through 2 types of vessel tracking systems: VMS and AIS. Both AIS and VMS data were granted by the ICM (*Marine Science Institute*).

3.2.1. AIS

AIS data was used to calculate fishing effort and make a comparison with VMS data. This data encompassed information from 2019 stored as twelve monthly ".csv" files, including position, time, speed and course variables of different vessels during a particular month[7].

First, the twelve files containing AIS raw data was processed using several functions found in the *AIS.py module*[8]. The frequency was reduced to 1 minute to minimize the computationally intensive data. AIS data were then filtered for trawling vessels using the European Commission's *Fleet Register* database[9]. Once this step was executed, another filter was required in order to know whether vessels were trawling or not, applying speed criteria when fishing (Oberle et al., 2016). The speed frequency of fishing vessels tends to follow a bimodal distribution; the first gaussian distribution corresponds to trawling speeds (low speed), and the second gaussian distribution to navigating speeds (high speed) (Shepperson et al., 2017). The outcome of the speed distribution of AIS data indicates that trawling speeds range from 0.8 to 3.9 knots (*Fig. 3.4*).

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[5] *Annex III* represents the seven fishing grounds in Palamós Canyon.

[6] *Annex III* represents the nine fishing grounds in Blanes Canyon.

[7] *Annex IV* shows a table with the different data collected in the AIS "csv." files.

[8] Algorithm used to perform the processing can be found in here: https://github.com/paradiss1/AIS_fishing_effort

[9] European Commission's *Fleet Register* database can be found in here: https://webgate.ec.europa.eu/fleet-europa/search_en

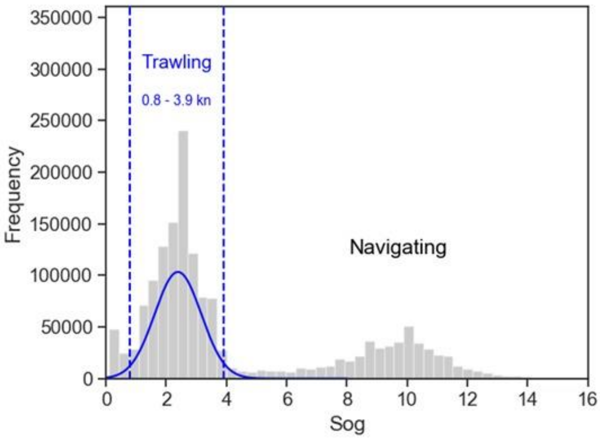

Figure 3.4. Gaussian model for AIS vessel data within 2019. Data acquired from ICM.

However, merely filtering vessels by trawling speeds may lead to false-positives and false-negatives. Firstly, to account for false-positives, it was assumed that continuous entries at trawling speed that lasted less than 10 minutes were not trawling. Secondly, to correct the false-negatives, it was presumed that a trawler could fish at higher/lower speed than the specified trawling speed in a haul for less than 5 minutes. Finally, to identify trawling activities, it was assumed that the duration of a haul was more than 100 minutes, meaning that if a trawler was moving at the specified trawling speed for over 100 minutes, it was trawling. To identify hauls, all the entries detected as trawling in a specific period were classified with a unique ID.

Processed AIS data was imported in ArcGIS and hauls were identified by connecting AIS points based on their haul ID. Fishing effort was obtained by calculating the density of hauls per hectare, to account for the average 100 m width of the trawling nets (Palanques et al., 2006).

3.2.2. VMS

The VMS files acquired encompass data between 2008 and 2019 about position, date, time, speed, and course of vessels[10]. This data was processed using the '*VMSbase*' package in R (Russo et al., 2014).

The first step consisted of creating a database and filtering out irregular pings through the cleaning option. The next step involved track cutting, which consisted of separating the VMS ping series by vessels. The resulting dataset was interpolated in 10 minutes intervals, considering the position, speed and course of the vessel, to reproduce in detail the track of the vessels as if they had sent their signals in a higher frequency (Russo et al., 2014).

Interpolated data points were then processed following the same procedure of the AIS dataset to ensure a comparison between both vessel positioning systems. The frequency distribution of VMS vessel speed recognised the range of trawling speeds between 1.5 and 3.7 knots (*Fig. 3.5a*). However, interpolated VMS data eliminated this bimodal distribution, rendering the identification of trawling speed unfeasible (*Fig. 3.5b*). Thus, VMS processing was reformulated, and the identification of trawling speed using bimodal distribution, as carried out with AIS data, was dismissed.

Hence, to recognise the parameters to be used in the haul identification algorithm, a thorough analysis of the interpolated VMS data was conducted by assessing the algorithm's performance in 8 random days. The results of this inspection focused on two aspects: the

[10] *Annex IV* shows a table with the different data collected in the VMS “csv.” files.

trawling speeds and the time considered to detect false-negatives. In terms of the speed, it was found that a proper approximation to trawling activities was to consider speeds from 1.5 to 5 knots (*Fig. 3.5b*). Speeds from 0 to 1.5 knots were excluded to avoid loops. Concerning the false-negatives, non-trawling conditions were converted to trawling conditions when these occurred between trawling conditions and lasted less than 20 minutes. As with the original AIS algorithm, false-positives were identified when trawling conditions lasted less than 10 minutes. Finally, continuous trawling conditions were assumed to be a haul when they occurred for at least 100 minutes.

Processed interpolated VMS data was then imported in ArcGIS and the temporal evolution of the fishing effort was determined following the same procedure employed for the AIS data.

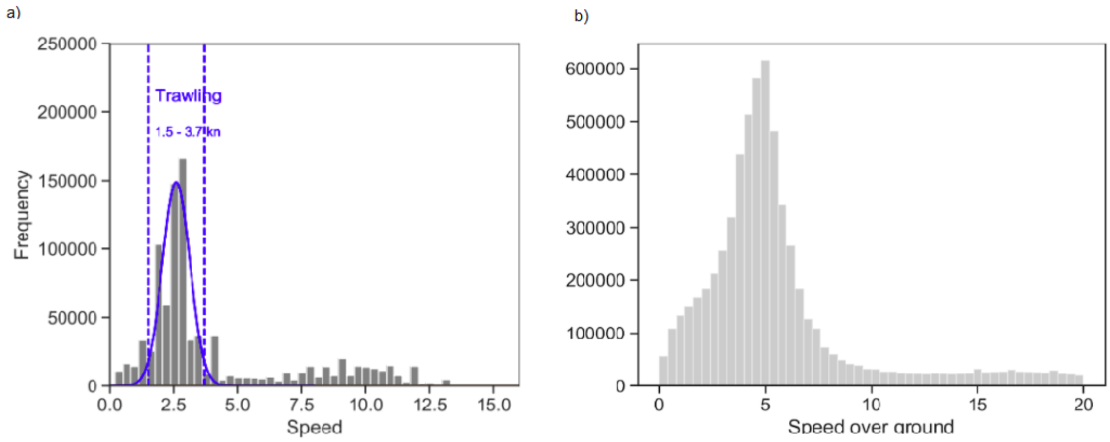

Figure 3.5. Histograms of vessel speeds. a) bimodal distribution of raw VMS data (within 2008 and 2019), b) bimodal distribution of VMS interpolated data (within 2008 and 2019). Data acquired from ICM.

3.2.3. VMS and AIS data treatment

An analysis between VMS and AIS data was developed by comparing the spatial extension of fishing grounds and fishing effort from January to August 2019. The spatial extension of fishing grounds was calculated by converting the density raster to a polygon file and quantifying the spatial extension of the resulting polygon.

After developing the VMS-AIS comparison, the temporal evolution of fishing effort over the years was developed using the VMS data. This analysis was structured around a complex map of yearly fishing efforts from 2008 to 2018. The extension of trawling grounds and the main fishing effort in the study area over the years was also evaluated following the same steps as the VMS-AIS comparative analysis.

The fishing ground areas of both Palamós and Blanes canyons were used to contrast the evolution in specific areas[11]. Average fishing effort (hauls/ha) were extracted from each fishing ground, excluding values equal to 0.

Finally, a seasonal analysis of fishing was elaborated to detect seasonality in the extension of trawling grounds: Winter (January, February and March), Spring (April, May and June), Summer (July, August and September) and Autumn (October, November and December).

[11] *Annex III* shows the fishing grounds in Blanes and Palamós canyons.

3.3. Video recording and analyses

In order to identify the geomorphologic changes and impacts of bottom trawling on the seabed benthic ecosystems, the Remotely Operated Vehicle (ROV) *Liropus* was employed to record visual data of the seafloor in September 2017 onboard the *R/V Sarmiento de Gamboa*.

The development of the present study compiled visual data of both canyons, Blanes and Palamós, each of which was divided into two transect lines (*Fig. 3.4*). In the case of Blanes Canyon, transect lines are named *Blanes 1* -on the Western part- and *Blanes 2* -on the Eastern part-. Similarly, in Palamós Canyon, the transect lines are called *Palamós 1* -on the Southern part- and *Palamós 2* -on the Northern part-. The transects' lengths ranged between 1.4 and 2.2 km, over depths from 900 to 400 m, approximately.

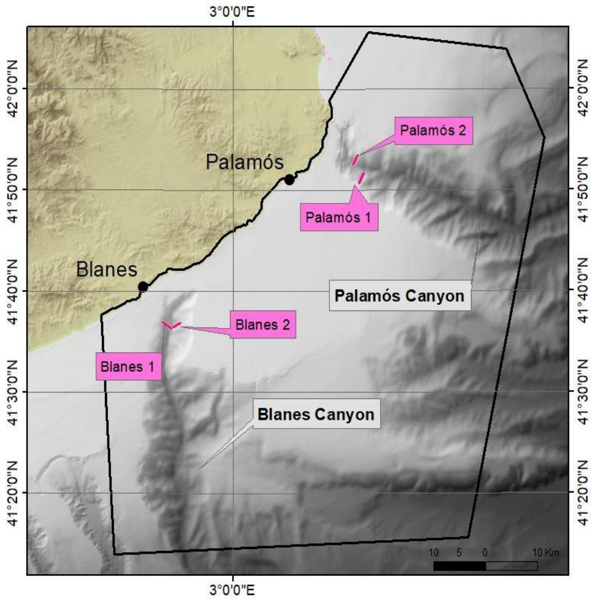

Figure 3.4. Sea bathymetry of the study area identifying the location of the Blanes 1, Blanes 2, Palamós 1 and Palamós 2 ROV transect lines. Data acquired from ICGC and ICM.

The analysed area in each of the videos was determined using the 10 cm laser beams' separation incorporated in the visual field of the recordings. Therefore, the total examined section covered 50 cm in length. Video observations were registered for each of the transects according to its timing, recorded either as intervals of time or specific timings. The duration of ROV stops were also marked down and were eliminated from the analysis. To compute the location of each observation within the transect, an approximation of the velocity of the ROV was first calculated using a uniform rectilinear motion equation ($v= x/t$), where the total length of each of the transects -which was estimated using ArcGIS- was afterwards divided by the total transect duration, excluding the stops. Finally, each of the specific locations was calculated as a simple multiplication of the velocity with the exact time of the events ($x= t \cdot v$). Data collected were divided into two types of observations (i) Seafloor typology and (ii) Biodiversity.

The different seafloor typology was classified according to three categories: rocky outcrop, non-impacted soft-bottom and impacted soft ground with trawl marks. Long line marks, profound and significant furrows, and some trawling litter were classified as trawling indicators. The observed features related to this section were contemplated as intervals of time.

Biodiversity, in turn, was divided according to the presence of animals and plants/algae. Each of the observations was catalogued in terms of the species and phylum or subphylum (Vertebrata, Cnidaria, Mollusca, Echinodermata and Annelida). The abundance of each phylum was extracted in 5 m^2 intervals along each transect. Additionally, the overall percentages of the total amount of observed individuals for each phylum during the video analyses were calculated and collected; polychaeta fields were analysed independently from Annelida phylum using time intervals. Cnidaria phylum was cautiously studied due to the inequalities in the motile capacity of the individuals of each class. Thus, the number of organisms for both Anthozoa and Scyphozoa classes were counted to understand posterior results of the abundance of the whole phylum on the transects.

A detailed profile of each canyon relating to the number of organisms, the seafloor type, the bathymetry and the fishing effort for 2017 was plotted. For the extraction of the fishing effort and bathymetry profile along the transects the *3D analyst* tool from the ArcGIS program was used, which generates a bathymetric and fishing effort profile of the transects.

4. Results

4.1 Fishing grounds

4.1.1. VMS and AIS data comparison

The comparison of VMS and AIS data showed a greater extension of trawling grounds extracted from the interpolated VMS data (120 hectares) in comparison to fishing grounds extracted from AIS data (82 hectares), showing that there were significant gaps in the AIS data surrounding Blanes Canyon *(Fig. 4.1).*

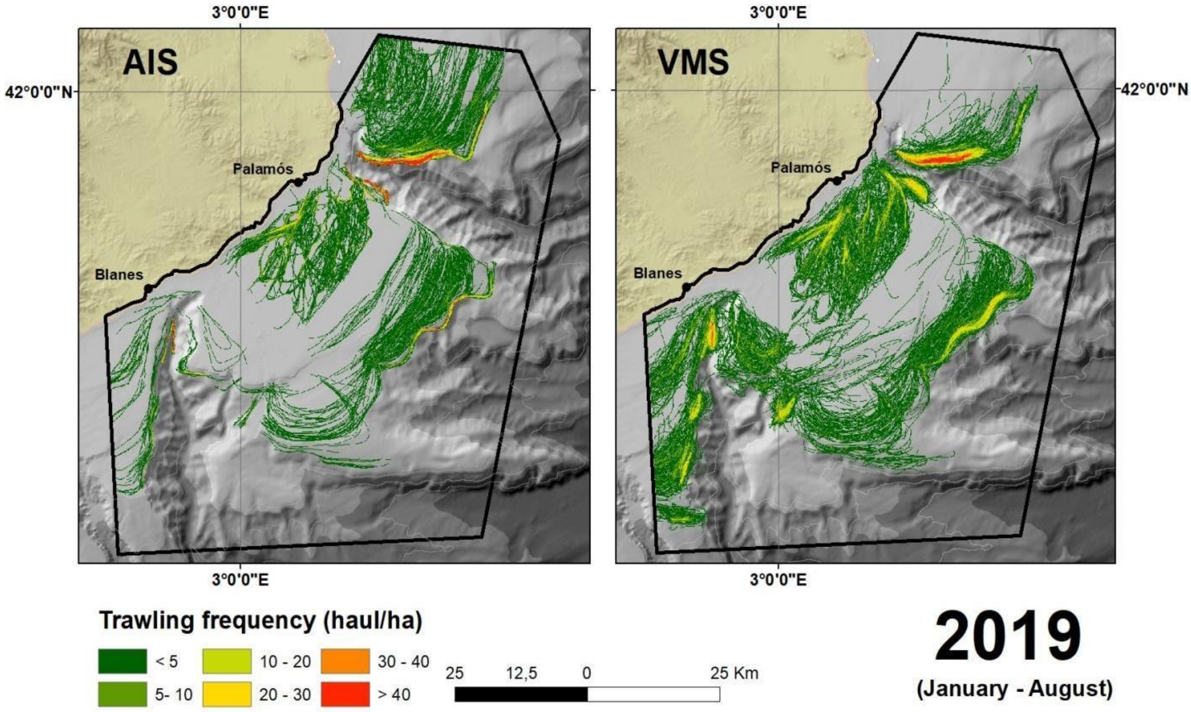

Figure 4.1. AIS and VMS comparison analysis through the fishing effort or trawling frequency, expressed in hauls/ha, during the year 2019. Data acquired from ICGC and ICM.

In terms of fishing effort, both methods averaged similar values (4.14 hauls/ha in the VMS data and 4.12 hauls/ha in the AIS data), although a higher maximum was observed in the AIS data (252 hauls/ha) in comparison to the VMS data (98 hauls/ha). Moreover, the comparison of the two maps showed that zones with high fishing effort (>10 hauls/ha) were lesser in the AIS map in comparison to the VMS map, which evidenced intense trawling activities around Blanes Canyon associated with high fishing effort *(Fig. 4.1).*

On the other hand, both AIS and VMS maps showed how Palamós Canyon had two recurrently visited fishing grounds with high fishing effort, coinciding with two fishing grounds named *Sant Sebastià* and *Rostoll*[12]. However, the northern open slope from this Canyon identified fishing activities in the AIS data that the VMS map overlooked.

[12] *Annex III* shows the different fishing grounds in Palamós Canyon.

4.1.2. Spatiotemporal evolution of fishing grounds through VMS data

The evolution of the fishing area over the last decade (2008-2018) revealed a general positive tendency, conforming to an overall increase of 19%. Between 2008 and 2015 the fishing surface expanded from 1,280 km^2 to 1,530 km^2. Afterwards, during 2016, there was a decrease reaching 1,420 km^2, followed by an increase to the stabilized value of 1,520 km^2 (*Fig. 4.2*).

Similarly, the evolution of the mean fishing effort also followed an upward trend. It began in 2008 with 3.87 hauls/ha, reaching in 2013 and 2017 a maximum of 5.43 and 5.52 hauls/ha, respectively. This positive evolution presented a momentous decrease in 2016, arriving at 4.5 hauls/ha. In this case, the overall increase from 2008 to 2018, was 37%.

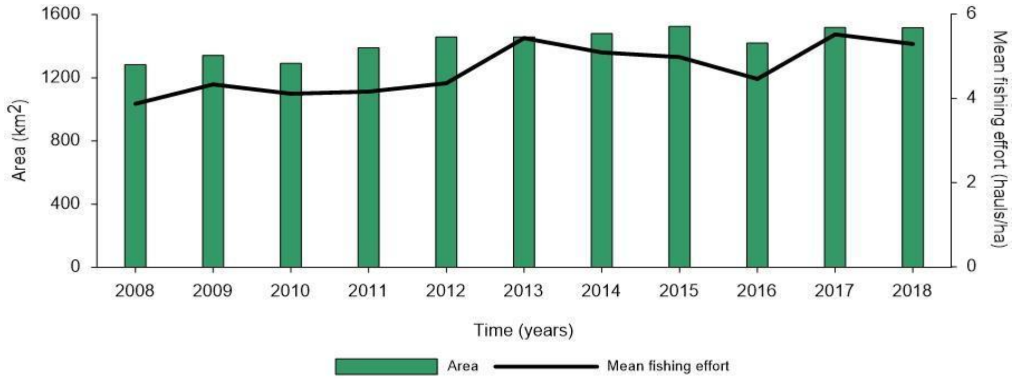

Figure 4.2. Evolution of fishing areas between 2008-2018 in the study zone, shown by the green bars. Also, the mean fishing effort of each year, shown with the green line tendency. Data acquired from ICM.

The seasonal analysis *(Fig. 4.3)* showed a general fishing area increase. Winter went from 280 km^2 to 412 km^2; Spring, from 545 km^2 to 721 km^2; Summer, from 550 km^2 to 823 km^2; and finally, Autumn from 353 km^2 to 662 km^2. Therefore, the increase in Winter was 47%, in Spring 32%, in Summer 50% and a greater increase in Autumn 87%.

Moreover, the analysis reflected a general pattern over the years. Winter months got the lowest fishing area values, followed by Autumn months, and reaching maximum values in Spring and Summer months. This general pattern was not representative of 2008 and 2017. In the case of 2008, Winter presented exceptionally high fishing areas, similar to those identified in Spring and Summer, between 500 and 600 km^2. In the case of 2017, the fishing area in Summer suffered a drastic decrease to 579 km^2.

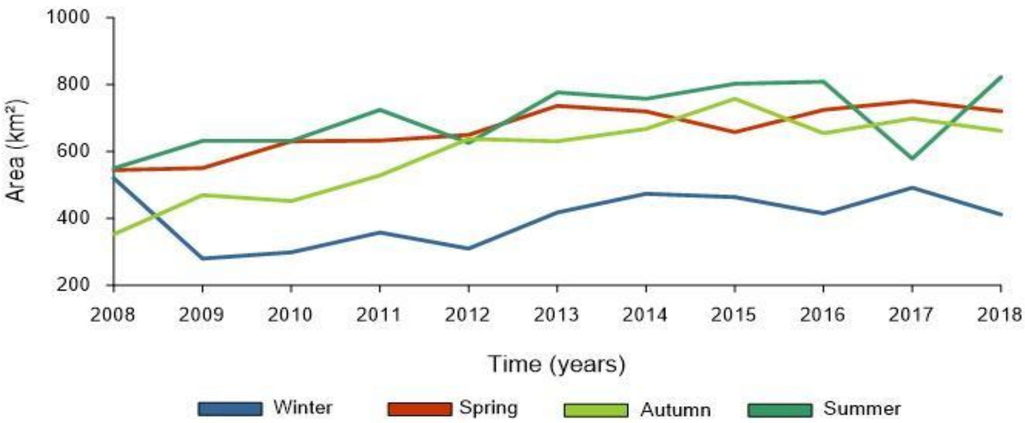

Figure 4.3. Evolution of the area over the four seasons of the year. Maps representing the values for each year are attached in Annex V. Data acquired from ICM.

The spatiotemporal evolution of fishing effort obtained from VMS data in the study area reflected a positive tendency over the years (*Fig. 4.4*). Palamós Canyon showed four areas with high fishing effort, coinciding with the fishing grounds called *Rostoll*, *Sant Sebastià, Llevant* and *Els Cots*. *Rostoll* is located in the southern flank, *Sant Sebastià* in the northern, *Llevant* perpendicular to *Sant Sebastià,* and *Els Cots* in a deeper zone between Blanes and Palamós Canyons. Similarly, Blanes Canyon presented four areas with high fishing efforts, which corresponded to *Rocassa, Rocassa de Llevant, Peneca*, and *Través* fishing grounds. *Rocassa* is located in the head of the canyon, *Peneca* in the western flank, and *Través* in the eastern. Besides, *Rocassa de Llevant*, relatively new, is located next to the original *Rocassa* and enters the head of the canyon, trawling in its interior.

Both Palamós and Blanes canyons withstood an increase in fishing effort throughout the years, except for 2016, when almost all fishing grounds suffered a decrease in fishing effort values *(Fig. 4.4, 4.5* and *4.6)*. It is important to differentiate between Blanes' and Palamós' evolutions, as each zone presented different results. While the overall fishing effort surrounding Palamós Canyon appeared to be high and consistent (ranging between 4 and 6 hauls/ha), Blanes did not show as higher values (central values between 2 and 3 hauls/ha). Nevertheless, Blanes Canyon contains the major fishing ground increase in the study area (*Rocassa de Llevant*).

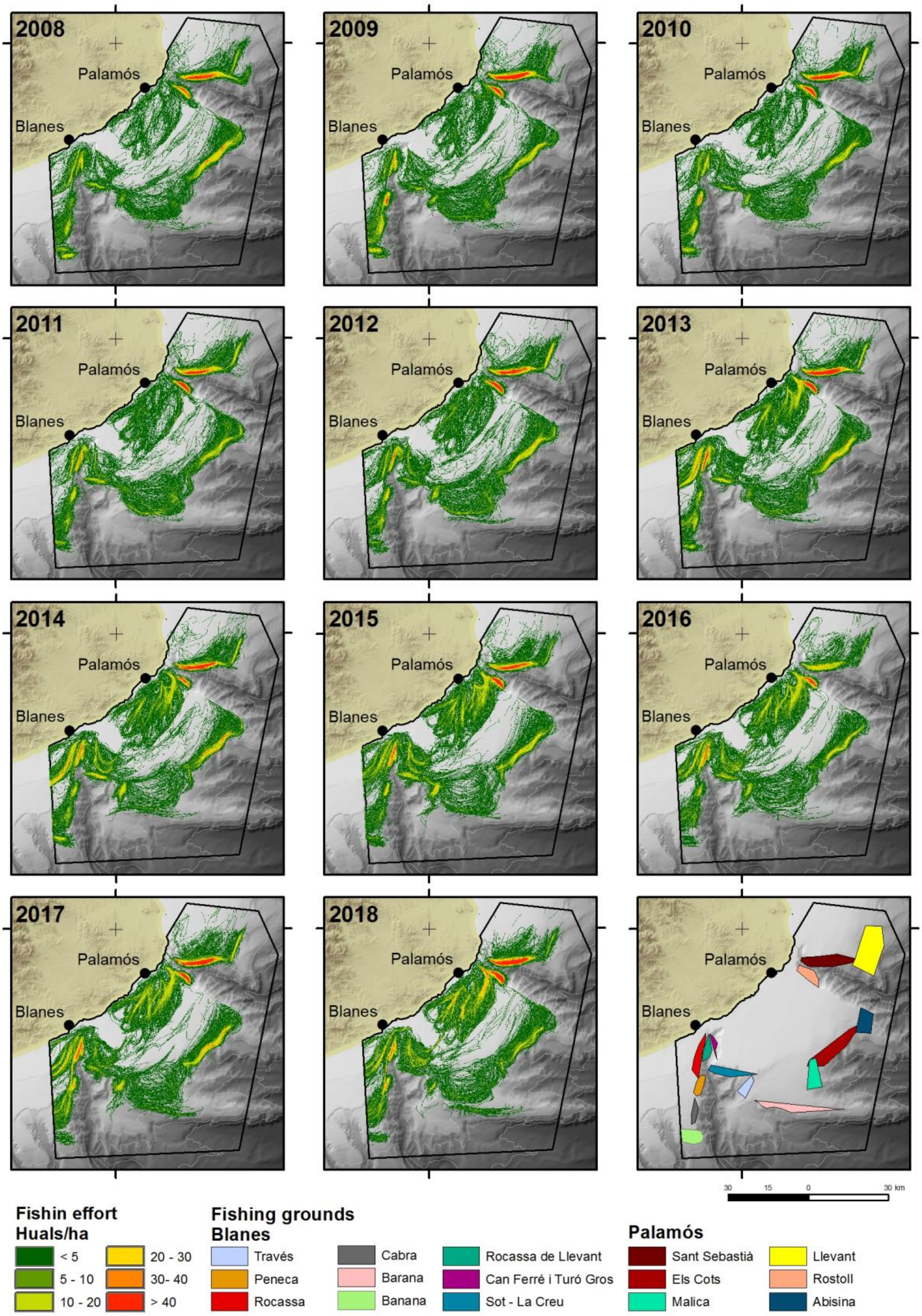

Figure 4.4. Spatiotemporal evolution of VMS data from 2008 to 2018. This figure gives information of the fishing effort (haul/ha) in the study area. 0 represents no fished areas, and 250 hauls/ha is the maximum unit. Consequently, green shows the lower fishing effort and red the higher. Besides, the last map represents the 15 fishing grounds in Palamós and Blanes. Data acquired from ICGC and ICM.

From the fishing grounds surrounding Palamós Canyon *(Fig. 4.5)*, *Rostoll* and *Sant Sebastià* presented the highest fishing effort values. *Rostoll* increased from 2008 (13 hauls/ha) to 2013 (27 hauls/ha). Thereafter, values fluctuated between 19 and 24 hauls/ha. *Sant Sebastià* fishing ground presented an intense fishing effort in 2008, which was maintained throughout the years (values ranging from 16 to 24 hauls/ha), except for 2016 (9 hauls/ha). *Llevant* fishing ground presented an apparent rotatory pattern, from the fluctuating fishing efforts (4-5 hauls/ha) between 2008-2010, to 6 hauls/ha in 2010-2013, followed by a decrease to 3 hauls/ha, and an increase to 6 hauls/ha in 2017. *Els Cots* reflected a stable evolution, with values ranging from 7 to 9 hauls/ha, reaching its maximum in 2017 (10 hauls/ha). Finally, *Malica* and *Abisina*, next to *Els Cots* fishing ground, showed constant development. In the case of *Malica*, there was an increase from 3 to 4 hauls/ha between 2008 and 2018. In the case of *Abisina*, there was a decrease from 6 to 2 hauls/ha during the same period.

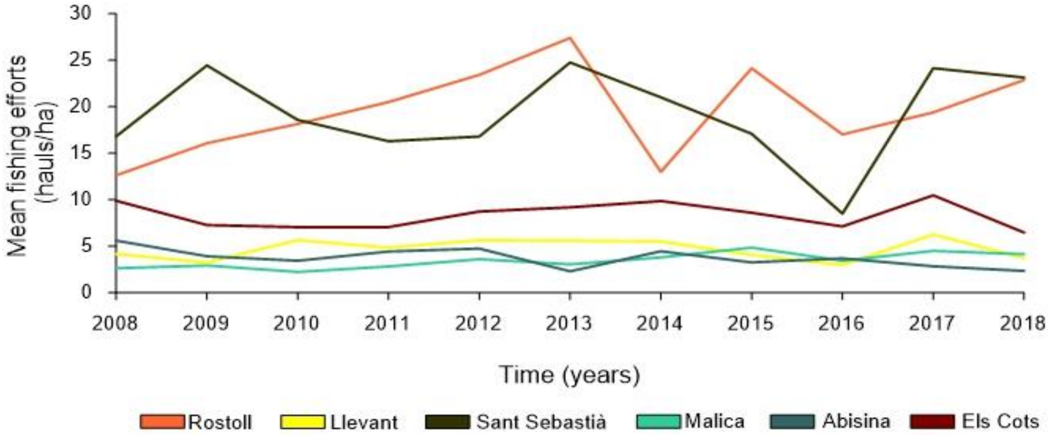

Figure 4.5. Analysis of the fishing effort on Palamós Canyon fishing grounds, between 2008 and 2018. Data acquired from ICM.

Besides, the area located on the shelf between Palamós and Blanes canyons, which has not been catalogued in *Figure 4.4*, presented a clear increasing tendency throughout the years. From 2008 to 2013, the fishing values were low and stable (<2 hauls/ha). The increasing tendency started in 2013 with values between 2 and 5 hauls/ha. In 2018, the range value was 5-10 hauls/ha.

From the fishing grounds surrounding Blanes Canyon *(Fig. 4.6), Rocassa de Llevant* encompassed the highest fishing effort, increasing from 8 hauls/ha in 2008 to 21 hauls/ha in 2013, after which values ranged between 14 and 18 hauls/ha. Similarly, *Rocassa* fishing effort increased from 2008 (7 hauls/ha) to 2013 (12 hauls/ha), followed by a decrease until 2018 (7 hauls/ha). *Través* presented stable fishing values from 4 to 8 hauls/ha, reaching two peaks in 2014 and 2015 with 9 and 10 hauls/ha, respectively. *Peneca* and *Cabra* reflected a similar evolution throughout the years. *Peneca* reached its maximum in 2009 (13 hauls/ha), followed by values between 6 and 11 hauls/ha. *Cabra* reached its peak in 2009 (11 hauls/ha), followed by values between 10 and 5 hauls/ha.

Sot - La Creu, Barana, Can Ferré i Turó Gros and *Banana* follow a roughly low and stable tendency. *Sot - La Creu* values went from 3 to 7 hauls/ha from 2008 to 2018. In the case of *Barana*, fishing effort ranged between 4 and 2 hauls/ha, reflecting the lowest values. *Can Ferré i Turó Gros* values went from 8 to 3 hauls/ha, with a peak in 2012 (10 hauls/ha). *Banana*, located between Blanes and Arenys canyons, showed values between 2 and 6 hauls/ha.

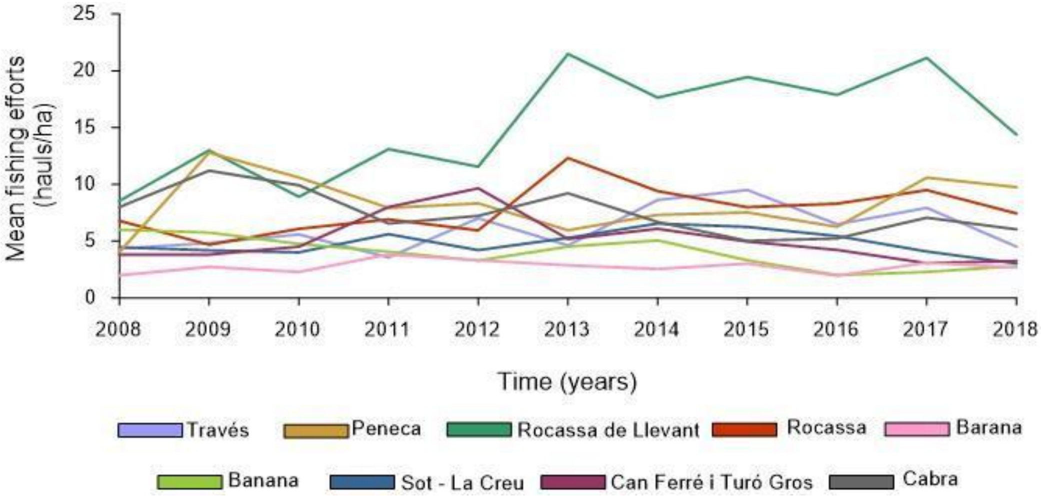

Figure 4.6. Analysis of the fishing effort on Blanes Canyon fishing grounds between 2008 and 2018. Data acquired from ICM.

4.2. Marine impacts

4.2.1. Geomorphological impacts

The analysis of the high definition videos acquired from ROV transects revealed remarkable dissimilarities between the four transects in terms of seafloor typologies. The seabed was classified according to the three seafloor typologies shown in *Figure 4.7*. Overall values of the percentage of seafloor covered by each category are also displayed in this figure. *Blanes 1* transect, crossing *La Rocassa* fishing ground, showed a high percentage of trawled seafloor, having almost 71% of its surface eroded and deteriorated. Rocky outcrops were practically absent, encompassing only 2% of the total transect. Non-impacted soft grounds covered the remaining 27% of the seafloor. Conversely, *Blanes 2* transect located on the outskirts of *Can Ferré* fishing ground is virtually formed by non-impacted soft seafloor, with a percentage of 91%. The remaining 5% and 4% is classified as rocky outcrop and impacted seafloor, respectively. *Palamós 1* transect, crossing *Sant Sebastià* fishing ground, is constituted by 18% of rocky bottom, 56% of non-impacted soft seafloor and 26% of impacted soft seafloor. *Palamós 2* transect, located on the edge of *Rostoll* fishing grounds, consisted of 4% of rocky bottom, 30% of impacted bottom and 66% of non-impacted soft bottom.

Figure 4.8 evinces a detailed view of the categorised seafloor types -rocky outcrop, soft-bottom and trawl marks- observed along each of the four transects. Fishing effort is represented by intervals, referring to different degrees of hauling pressure. It is worth noticing the correlation between the highest values of the fishing effort and the impacted areas.

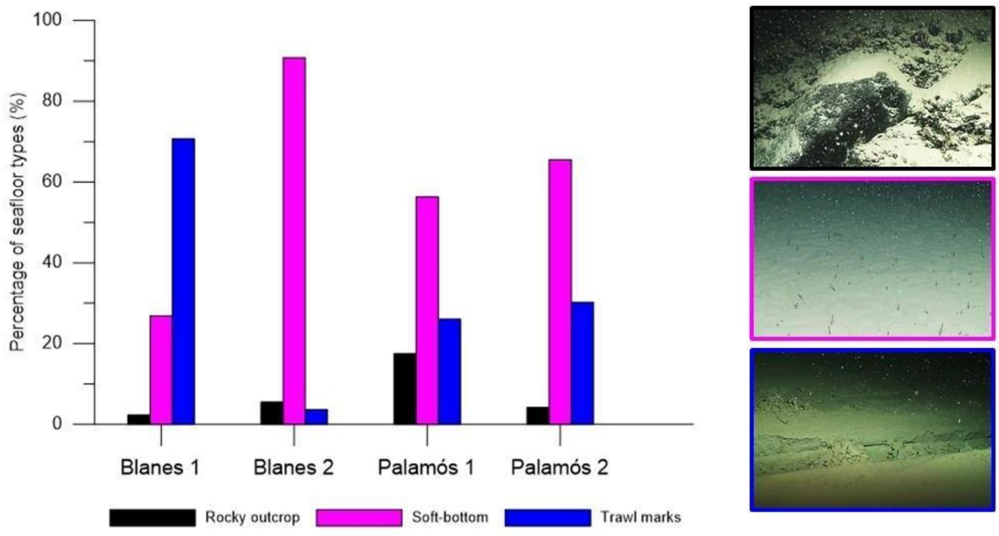

Figure 4.7. Different percentages of each soil type (rocky outcrop, soft-bottom, trawl marks) for each of the analysed transects in September 2017. Trawl marks were only observed on muddy seafloor. Data acquired from ROV video recording observations.

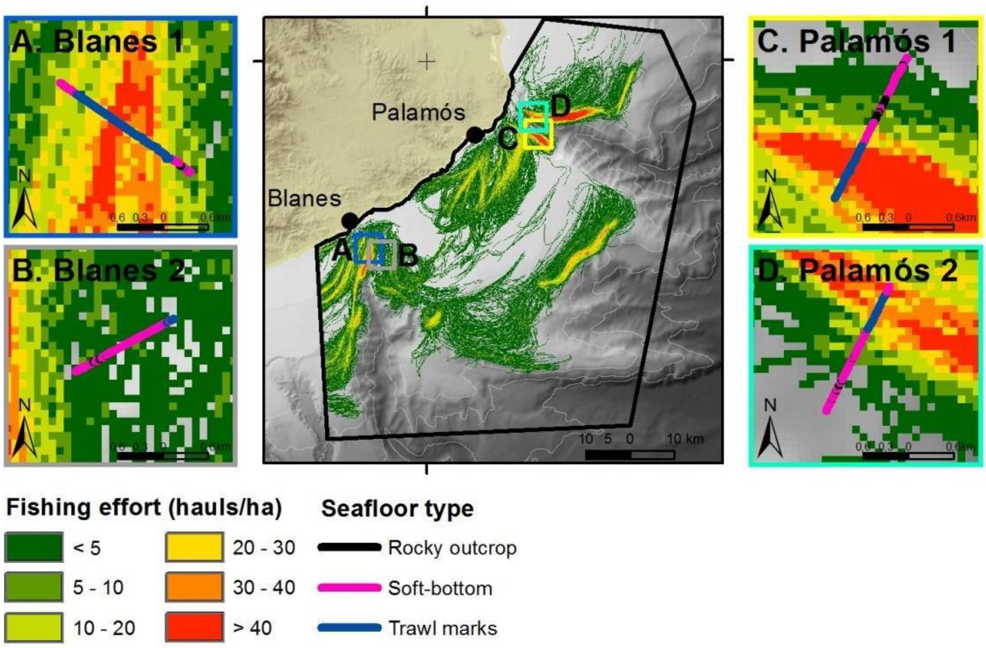

Figure 4.8. Map of the different soil types (rocky outcrop, soft-bottom, trawl marks) for each of the analysed transects, related to the fishing effort in September 2017. Data acquired from ROV video recording observations, ICGC and ICM.

4.2.2. Ecological impacts

The encountered phyla were similar in the four transects (*Fig. 4.9a*). The phyla (or subphyla) encompassing a major number of individuals in the study area were Vertebrata, Cnidaria, Crustacea, Annelida[13] and Echinodermata, being Crustacea one of the most prevalent and Annelida the least present. Nevertheless, the abundances for each phylum differed notably depending on the transect.

[13] In the present study Annelida phylum does not encompass polychaeta fields.

In *Blanes 1*, the majority of individuals were Vertebrata and Crustacea (35% and 34%, respectively), whereas the 20% of species were cnidarians. Annelida and Echinodermata only corresponded to 6% and 4% of the organisms, respectively. In *Blanes 2* transect, 31% were cnidarians, the most abundant phylum, followed by Crustacea (26%), Echinodermata (20%) and Vertebrata (16%), whereas only 9% of the individuals were Annelida.

Palamós 1 transect was characterized by having a considerable biomass of crustaceans (33%) and echinoderms (25%). The third most abundant subphylum is Vertebrata, with 20% of the identified organisms, followed by Cnidaria (18%) and a minor presence of Annelids (4%). *Palamós 2* contained 36% of vertebrates. The abundance of crustaceans and cnidarians is similar, with values of 26% and 22%, respectively. Echinodermata phylum showed a percentage of 9% and Annelida were present at 5%.

The motile capacity of the organisms of each class was studied through the phylum Cnidaria (*Fig. 4.9b)*. Thus, the number of organisms for both Anthozoa and Scyphozoa classes were counted. Generally, the abundance of sessile and retractile anthozoan organisms was higher than mobile scyphozoan individuals for all the transects excluding *Blanes 1*. The transect encompassing a major number of anthozoan individuals in the study area was *Blanes 2*, where 30 of the 35 cnidarian organisms assessed along the transect corresponded to the class Anthozoa. However, the transect encompassing a major number of Scyphozoa individuals was *Blanes 1,* embracing 12 of the 25 cnidarian organisms.

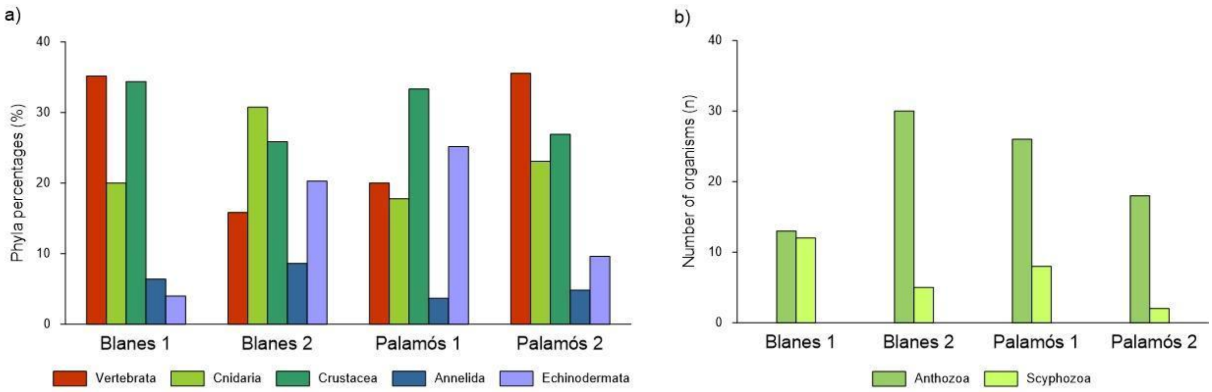

Figure 4.9. a) Different percentages of each phyla or subphyla (Vertebrata, Cnidaria, Crustacea, Annelida, Echinodermata), for each of the analysed transects in September 2017. b) Different number of Anthozoa and Scyphozoa cnidaria individuals for each of the analysed transects in September 2017. Data acquired from ROV video recording observations.

Figures 4.10 and 4.11 displays a complete profile of the abundances for each phylum or subphylum (Vertebrata, Cnidaria, Crustacea, Echinodermata and Annelida) along the four transects including information referring to the bathymetry, fishing effort of 2017 and seafloor type. The abundance of organisms did not present a clear trend with depth. Impacted areas presented a generally lower number of organisms which generally coincided with the shallowest parts of the transects and the highest fishing effort.

In *Blanes 1*, fishing effort pressure was especially remarkable. Although not having the highest values, they were the most constant and stable, which provoke negative consequences on the seafloor (*Fig. 4.7*) as well as on the living organisms. Lowest values of the abundance of all individuals were found at depths ranging 750 m and 500 m, in coincidence with the presence of trawl marks and highest values of the fishing effort (*Fig. 4.10*). In this transect, echinoderm and annelid individuals were only present at 500 m and 300 m water depths, where fishing effort was lower and trawl marks were absent.

Blanes 2 transect is characterized by having the higher percentage of soft-bottom seafloor type with fishing effort values close to zero (*Figs. 4.7 and 4.10)*. In terms of biodiversity, the most abundant phyla were Cnidaria and Crustacea (especially between 600 m and 500 m depth), whereas Annelida was the less abundant one, being only present between 700 m and 600 m depth. The deeper section of the transect (700 - 620 m depth) shelters the major number of organisms for the five phyla. Nevertheless, there is a conceivable gap between 620 and 535 m depth.

Both *Palamós 1* and *Palamós 2* transects showed a high and constant number of vertebrate organisms. Trawl marks were prominent on the shallowest area of the transects, coinciding with the highest fishing pressure. Fishing pressure in Palamós became noticeable in waters shallower than 750 m depth.

When it comes to Palamós *1* transect, although presenting a relatively low number of hauls per hectare during the majority of the transect length, it presented a noteworthy fishing effort maximum (~100 hauls/ha). Its biodiversity was characterized by the high number of echinoderms (31 organisms) gathered at the beginning of the transect, between 1000 and 750 m depth, where the fishing effort was virtually absent. Crustaceans, in contrast, are mostly found throughout the last meters of the transect, which concurs with the highest fishing intensity. It is worth mentioning the presence of polychaeta fields along the first 275 m approximately (below 750 m depth).

Living fauna in *Palamós 2* transect is mostly encountered at depths ranging between 800 m and 650 m, coinciding with the lowest fishing effort values. Nonetheless, echinoderms mostly inhabited depths of 600 m. After remaining stable during the previous sections, fishing effort increased to its highest values at 400 m depth, generating a considerable gap of organisms during the last meters of the transect. Polychaeta extensions are also visible sporadically during the first 1,380 m of this transect and in non-impacted zones (below 600 m depth).

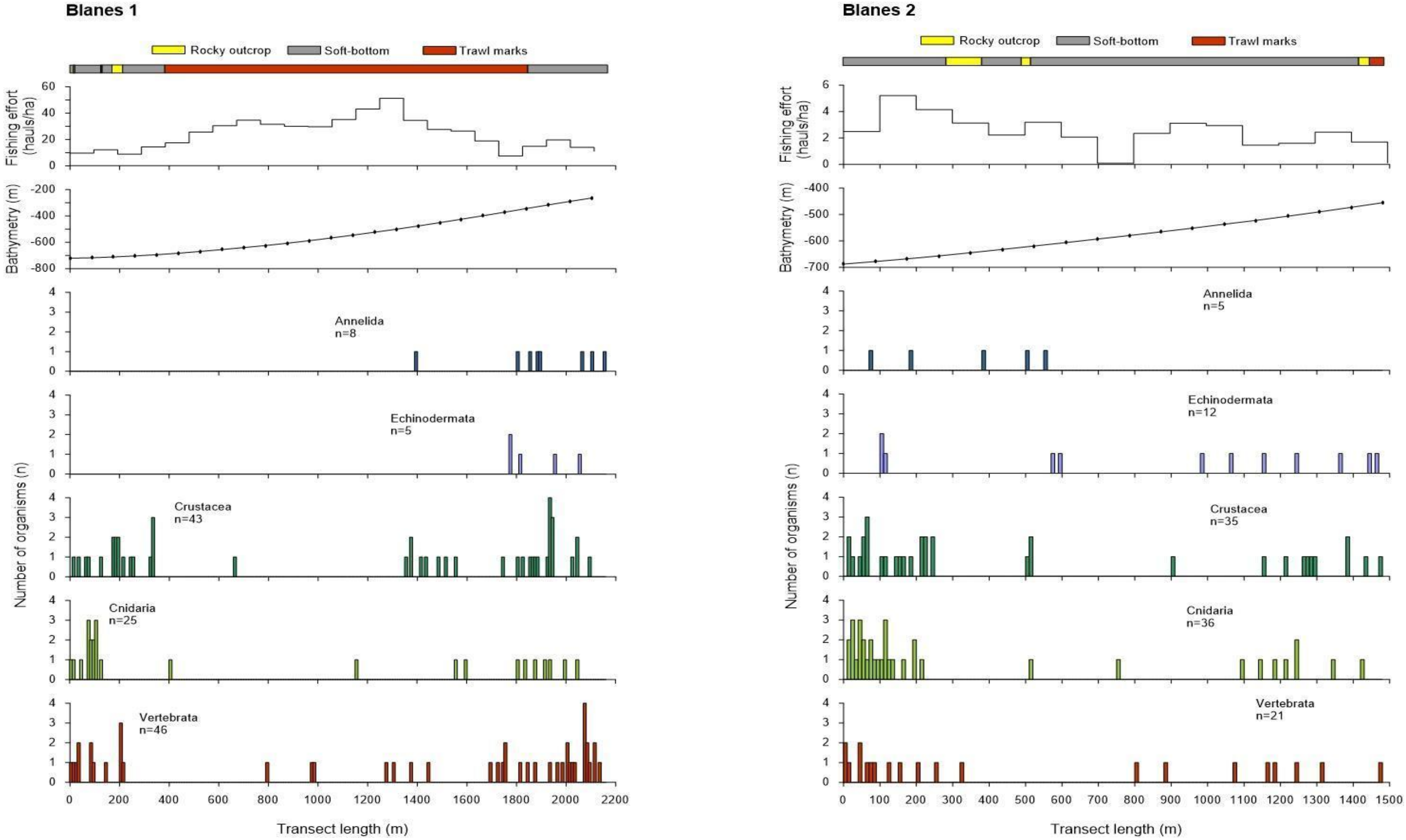

Figure 4.10. Number of organisms for the five different phyla or subphyla on each transect (Blanes 1, Blanes 2). Additional information referring to the bathymetry, fishing effort of 2017 and seafloor type is included. Data acquired from ROV video recording observations and ICM.

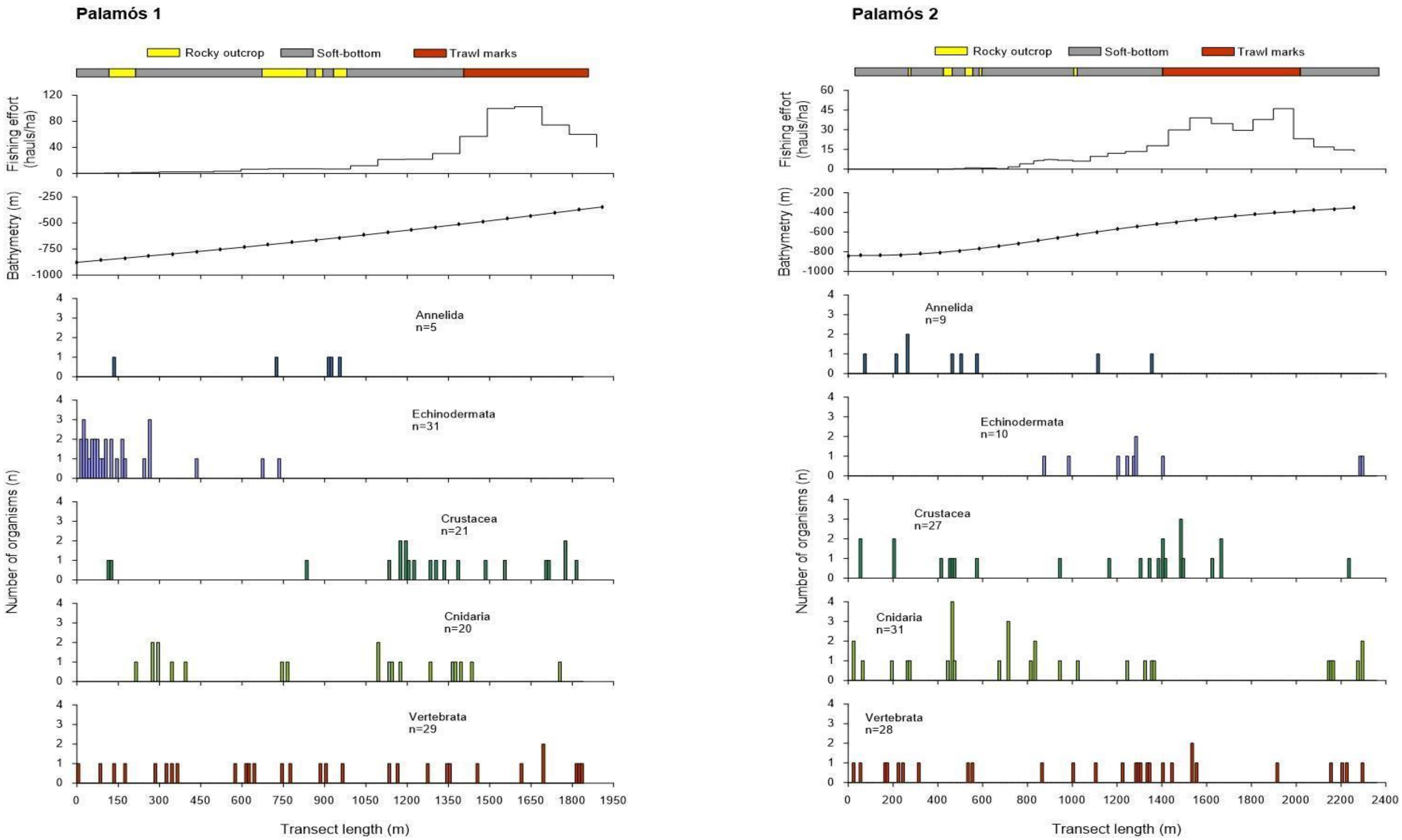

Figure 4.11. Number of organisms for the five different phyla or subphyla on each transect (Palamós 1, Palamós 2). Additional information referring to the bathymetry, fishing effort of 2017 and seafloor type is included. Data acquired from ROV video recording observations and ICM.

5. Discussion

5.1. Comparison of VMS and AIS data

The technical definition of fishing effort used in this project is related to understanding and quantifying the impact of bottom trawling on the seafloor. Many studies calculate fishing effort as hours/km^2/year in order to relate to the effects on stock exploitation (Natale et al., 2016; Kroodsma et al., 2018); however, since this study aims to identify zones with high impacted seafloor, fishing effort is described as the number of hauls in a defined surface area. If the number of hauls in an area is high, fishing effort is high, meaning that a large number of vessels and their trawling gear have passed through that zone, affecting the seafloor.

VMS and AIS monitoring systems are useful tools when interpreting fishing activities. Unlike AIS data, the time resolution of raw VMS data is given every 2 hours, which does not allow the identification of fishing vessel tracks. For that reason, an interpolation method needed to be executed, which reproduced the track of the vessels taking into account its position, speed and course at a higher frequency (Russo et al., 2014). Nevertheless, the interpolation of VMS data as a way of approximation to the vessel tracks may have introduced errors, diminishing the reliability of this dataset. As a consequence of the interpolation method and the algorithm used in VMS data, a different bigaussiant scheme was generated (Shepperson et al., 2018), and the fishing speed needed to be redefined from the one established for AIS data (*Fig. 3.5*). Trawling velocities for interpolated VMS ranged from 1,5 to 5 knots, in agreement with fishing velocities used by European trawlers (Natale et al., 2015; Shepperson et al., 2018). Hence, the new velocities range -derived from the interpolation process- could have induced errors, classifying real non-trawling hauls as trawling, and trawling hauls as non-trawling.

One of the aims of this study is to highlight the differences in data coverage between the two monitoring systems. AIS data has a substantially lower coverage than VMS data and, thereby, provides a potential underestimation of the overall activity. Since AIS data is an open vessel tracking with no encryption, it is sent by the vessels omnidirectionally. Therefore, it can be received by other ships in the vicinity, by ground-based receivers and satellites. Occasionally, some vessels are out of range, and consequently some data is lost. Every vessel can access AIS data from other vessels *in situ* to avoid collisions, as well as turn down manually the AIS transmitter (Natale et al., 2015; Russo et al., 2016).

Results from the present study have shown that the mean fishing effort obtained in the study area is almost equal in both VMS and AIS, being in that case both monitoring systems comparable. However, in terms of fishing area *(Fig. 4.1)* the results obtained differ between VMS and AIS.

In Palamós Canyon, the density of VMS lines representing fishing effort highly coincides with the fishing effort of AIS data (*Fig. 4.1*). However, in the upper northern part of Palamós Canyon, the algorithm of VMS does not capture certain fishing activities that are present in the AIS data as a zone with low fishing effort (<5 hauls/hectare). This gap of VMS data could be attributable to either an error in the interpolation method or in the velocity chosen to identify fishing activities, as previously mentioned (*Fig. 3.5*).

Regarding the Blanes Canyon, there is a substantial gap in AIS data compared with VMS data in terms of the fishing area, generating a low density of AIS data and resulting in a considerable underestimation of fishing activities. This low density of data could be attributable to vessels that fish far away from the coast and, consequently, the loss of data is high (Russo et al., 2016). However, these fishing grounds are located close to shore, at less than 4 km, similar to Palamós fishing grounds, making this assumption unreasonable. A more plausible explanation for the low representation of fishing ground around Blanes Canyon would be that vessels fishing in this area turn off the AIS transmitter. Vessels turn off the transmitter for different reasons (i) avoid detection while undertaking an illegal fishing activity and (ii) preventing other fishers from identifying new fishing grounds (Shepperson et al., 2018). Hence, AIS data provides insufficient data to estimate the extent or intensity of fishing for fishing fleets operating in trawling grounds surrounding Blanes Canyon (*Fig. 4.1*).

These results are in agreement with previous studies that compare the efficiency of AIS and VMS data, which prove that AIS greatly underestimate trawling effort (Russo et al., 2016; Shepperson et al., 2018). However, these studies did not consider that the inconsistency between AIS and VMS may be due to a greater tendency of certain fishing fleets to turn off their AIS. Although the present results indicate that trawling fleets operating in the vicinities of Blanes Canyon are not properly represented using AIS data, more studies are needed to confirm this. Nevertheless, it should be noted that the possibility of comparing different types of data provided by each monitoring system gives much essential information that can be missed by employing only one monitoring system (Russo et al., 2016). Considering the lack of proper representation of fishing fleet data using AIS data, the analysis of fishing evolution in the past decade was carried out with VMS data.

5.2. Spatiotemporal evolution of bottom trawling

The general trend observed in the time-series analysis shows an increase of the fishing effort from 2008 to 2018 within the extension of the fishing grounds (*Fig. 4.2*). Gorelli (2016) recorded an increase in fishing effort and catch per unit of effort (CPUE) in the Northwest Mediterranean, proving overfishing of the red shrimp *(Aristeus antennatus)*, related to a decrease in the CPUE over the years (1963 to 2013). This CPUE reduction and the fishing effort increment not only entails greater risks of stock overexploitation, but also higher impacts on the seafloor. Connecting this with the results developed in the present study, the CPUE decrease could also be associated with the search of new fishing grounds, specifically noticed in *Rocassa de Llevant*, which opened in 2006 (P. Puig, personal communication), and increased its occupation considerably over the years (*Fig. 4.4*). In contrast, *Rocassa* and *Peneca*, which are historic fishing grounds, reflect an apparent decrease. Moreover, the opening of *Rocassa de Llevant* manifests a higher interest in deeper areas to fish, in this case, in the upper canyon axis. This fishing tendency over deeper zones has been analysed by several studies, as this is a global phenomenon (Morato et al., 2006).

The seasonal analysis shows a general pattern over the years; Winter is the season with the lowest fishing values *(Fig. 4.3)*. This condition is closely related to two facts. Firstly, the Winter season is characterized by storms and adverse conditions to fish. Secondly, every year, fishing bans imposed by the government are established between January and March (*Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente,* 2020). Moreover, the fact that these bans are established in Winter can be directly linked to marine ecosystem fragility in this season. Company (2003) reported that *A. antennatus* species present the highest number of juvenile individuals during Winter. Hence, the protection and growth assurance of the juvenile population could be the motive of establishing the fishing ban in Winter. Consequently, letting the shrimps grow in Winter ensures a win-win situation for the fishers, who catch grown shrimps with higher prices, and for the ecosystem, which takes a break in this period and recovers.

Although VMS data stems from vessels coming from many places over the Catalan coast, fishing values can be analysed through Blanes and Palamós particular fishing fleet. Thus, it is crucial to notice how fishing values in Blanes Canyon are lower than those of Palamós.

This circumstance agrees with the harbour registries, which remark the more numerous trawling community in Palamós (*Situació de la flota pesquera*, 2020)[14].

The most popular fishing grounds in Palamós Canyon are *Rostoll* and *Sant Sebastià*, as they are close to the coast and fishing here represent low fuel consumption (S. Paradis, personal communication*) -Figs. 4.4* and *4.5* reflect their high fishing values-. *Els Cots*, *Abisina,* and *Malica*, located 35 km from the coastline, between 500 m and 1000 m depth, were very relevant in the past; fishers started exploiting them in 1930. The name of *Abisina* is probably related to the word abyss, which reflects the principal characteristics of this place, deep and far from the coast (*Congrés Internacional de Toponímia i Onomàstica Catalanes*, 2001). It is worth noticing how these three fishing grounds, dominated by *Els Cots*, present a rotatory evolution throughout the years, illustrating a low but constant fluctuation. Finally, *Llevant* manifests a constant decrease throughout the years, possibly becoming a neglected fishing ground in the early future.

In the case of Blanes Canyon, *Rocassa de Llevant* represents the most trawled fishing ground, followed by *Rocassa, Través,* and *Peneca*. It is noteworthy that *Rocassa* and *Rocassa de Llevant*, located nearby, perform a parallel evolution, reflecting a particular interconnection (*Fig. 4.6*). The main difference between them is the fishing values and the depth, which are both higher in *Rocassa de Llevant*. While these two nearby fishing grounds reflected a yearly decrease in 2012, *Can Ferré i Turó Gros* and *Través* reach a maximum. This circumstance can be explained as a catch decrease in the principal fishing grounds and the search for a less-visited trawling ground to obtain more significant catches. In contrast, *Sot - La Creu, Barana, Cabra*, and *Banana* fishing grounds reveal a neglected trend, manifesting low values, probably related to a distant location from the coast and the fact that *Rocassa de Llevant* is replacing them.

5.3. Effects of bottom trawling on the seafloor

Bottom trawling affects seafloor morphology by replacing natural bioturbation mounds to series of trawl marks on muddy seafloors, since rocky outcrops are not suitable grounds for fishing (Buhl-Mortensen et al., 2013). However, many studies question the reliability of trawl mark densities as indicators of fishing intensity, since trawling impacts can vary depending on hydrodynamic processes, bioturbation degree, type of sediment and fishing pressure (Mérillet et al., 2018). For instance, Buhl-Mortensen and Buhl-Mortensen (2018) did not observe a strong correlation between fishing intensity and number of trawl marks when studying the seabed in Norwegian waters due to variations in the sediment type. This fact recalls the importance of understanding the global system and the multiple factors that can lead to dissimilar results. The findings of this study reflect a highly impacted seafloor in *Blanes 1*, with an elevated number of trawl marks. These results are also found in the shallowest depths of *Palamós 1* and *Palamós 2* in a similar way. Conversely, *Blanes 2* is essentially formed by soft-bottom non-impacted seafloor.

As previously mentioned, the analysed ROV videos were recorded in September 2017. This year had the highest registered values of fishing intensity within the studied decade (*Fig. 4.2*). In terms of total fishing area, it suffered a noticeable decrease during that Summer, with a reduction of more than 220 km^2 of its initial surface. Therefore, due to the long-lasting attribute that characterize trawl marks on deep environments (Ball et al., 2000), the observed features might be slightly more accentuated than during the previous months. A closer

[14] *Annex I* shows a table in which the fishing fleet evolution from both, Blanes and Palamós harbours is reflected.

temporal analysis would provide a better understanding of the impact generated and accumulated by bottom trawling activities and the recovery capacity of the seafloor.

It is also worth noticing the correlation between impacted areas and high values of fishing effort recorded in September 2017, as well as non-impacted areas and low fishing effort values, especially in *Blanes 1, Palamós 1* and *Palamós 2* transects. *Blanes 2* transect, located on the outskirts of *Can Ferré i Turó Gros* fishing ground, is virtually formed by non-impacted soft ground seafloor, thereby, trawl marks are almost non-existent all along this transect. Nonetheless, fishing effort estimations indicate that trawling is performed on all sides of the canyon, with values ranging between 2 to 3 hauls/ha during 2017. This can be a result of a notable peak observed in this fishing area in 2012, followed by a minor increase of hauls noticed during 2014. The tendency followed a slight decrease since then, still showing signs of fishery pressure. As Ball et al. (2000) stated in previous studies, trawl marks can persist up to 2 years in muddy substrates. Nevertheless, these durations can vary depending on several factors, such as sedimentation rates or storms, which can redistribute sediment along this margin (Sanchez-Vidal et al., 2012). Hence, one possibility for the discordance between the fishing effort and the absence of trawl marks along *Blanes 2* transect can be the natural dynamization or derived physical sediment resuspension and posterior transport from shallow waters to deeper waters (Sanchez-Vidal et al., 2012), which could erase trawl marks generated by the high trawling pressure recorded in 2014.

As it has been previously introduced, the persistence and penetration of trawl marks may vary depending on the sediment size (Buhl-Mortensen and Buhl-Mortensen, 2018; Mérillet et al., 2018). These physical disturbances are known to be less accentuated on coarse sediments as a result of the lower cohesive strength between the particles. Following this statement, the lack of trawl marks in this transect could be attributed to differences in grain sizes (i.e. particles of greater diameter), which would need to be confirmed by analysing grain size fraction of sediment in this area. Moreover, the presence of bioturbators, which are abundant throughout *Blanes 2* transect, can also contribute to stirring the upper sediment layers which would erase any visible trawl mark (Mérillet et al., 2018).

The mentioned discordance can also be traceable to the distinction of seafloor types used in this study. Whereas rocky outcrop, soft-bottom and trawl marks were classified as seafloor types, the sweeping action of trawls was not considered as a potential impact on the seafloor. Furthermore, despite going unnoticed during ROV video observations, trawl marks can still remain visible in sonographs, which recognize sediment structure and density (Palanques et al., 2001). The incorporation of this new type of seafloor alteration and the sonographs could provide a more comprehensive geomorphological results on the study area.

A comparison between 2017 and 2018 in terms of fishing effort and type of seafloor could be significant in order to foresee new potentially impacted or non-impacted areas. The unavailability of data from 2019 makes it hard to predict the current state of the seafloor around Blanes and Palamós canyons. However, observing the general trend of the most recent year with available data (2018), it is expected to find an equally degraded seafloor on both Palamós and Blanes canyons over the next few years; since virtually almost all the lines representing the fishing effort for 2018 on *Figure 4.5* and *4.6* present the same values and tendency as in 2017. Notwithstanding, Palamós trawling grounds present higher fishing effort values than Blanes'. A closer sedimentological analysis (e.g. organic material content and push-cores) would provide a better understanding of the sedimentological condition associated to greater fishing intensity (*Fig. 4.7)*.

Despite the general similar trend of fishing effort values in 2018 compared to the 2017 ones, it is also notable the upward trend of *El Rostoll* (located in the edge of *Palamós 2* transect) from 2016 onward, which suggests that seafloor from this canyon could continue suffering from further erosion and degradation.

5.4. Alterations of megafaunal diversity by bottom trawling

Previous studies demonstrated variations in biodiversity between canyons situated within the Catalan margin (i.e. differences in species biodiversity between Blanes and Merenguera canyons) (Ramirez-Llodra et al., 2009), but differences in terms of megafaunal total abundance and faunal composition between Palamós and Blanes submarine canyons were absent. In fact, variations in megafaunal diversity were mostly driven by the presence of bottom trawling (Kaiser et al., 2000; Pusceddu et al., 2014; Clark et al., 2016).

It is worth noticing that fishing effort values at depths greater than 750 m are practically absent in both canyons, which indicates that bottom trawling is limited to this depth. In legislative terms, it is postulated in BOE (*Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente*, 2018) that red shrimp trawling ranges between 300 and 1,000 m depth. Indeed, Blanes' red shrimp fisheries are known to operate between 600 and 800 m depth (Ramirez-Llodra et al., 2009). This fact is clearer for Palamós' fishing fleets than for Blanes' fisheries, yet a similar bathymetric threshold might be expected in the latest one. Therefore, fishing intensity is concentrated on the shallowest parts of the transects, coinciding with the most prominent trawl marks and lowest values of organisms, especially the sessile and retractile species.

Although having a similar number of individuals, biodiversity patterns differ depending on the transect and its trawling pressure. This is a result of the considerably negative relationship between fishing effort and diversity of megabenthos on the analysed submarine canyons (*Figs. 4.10 and 4.11)*. Seafloor with lower trawling intensity (most of *Blanes 2* transect, for instance) have a greater biodiversity, whereas heavily trawled areas encompass a more uniform fauna. Canyons generally tend to foster greater benthic macrofaunal abundance, known as the "canyon effect" (Gili et al., 1999), but this effect may be reduced by the intense bottom trawling activities in both Blanes and Palamós canyons. Similarly, Ramirez-Llodra et al. (2009) reported a decline of the 'canyon effect' for benthic megafaunal abundance in Blanes Canyon in comparison with Merenguera Canyon, where trawling is not as intense as in Blanes Canyon. In the previous study, a diminishment of the carrying capacity of populations was attributed to chronic fishing pressure over these benthic communities. A closer analysis of the different species would provide a greater insight of the effects of continuous bottom trawling on biodiversity. In fact, species within the same phylum may have different mechanisms to survive intense bottom trawling activities such as higher mobility or the capacity to retract and/or burrow, as described by Clark et al. (2016).

Continuously fished zones are mostly dominated by species with high resilience and ability to adapt to anthropogenic physical disturbances (Kaiser et al., 2000), such as decapod crustaceans and fish (Sardà et al., 2009). This statement is reflected in the results, since fish and crustaceans (mainly decapods) are more likely to inhabit trawled areas. However, as it has been previously mentioned, the stock of recurrent trawled zones is in decline. As a consequence, fishing fleets are moving to deeper and newer areas to capture target species, as for example the red shrimp (*A. antennatus)* in *Rocassa de Llevant*.

The bathymetric range where phyla are encountered and its abundance along the transects has also been analysed. Note that bathymetry plays an important role regarding faunal communities, yet fishing activities might alter this pattern (Roman et al., 2018). On the one hand, vertebrates, cnidarians and crustaceans are found homogeneously all along the specific study site and depths. Due to the ecological capacity of vertebrates and crustaceans, organisms from these phyla are able adapt to a wider range of depths (Sardà et al., 2009). On the other hand, echinoderms and annelids are mostly present at the latest metres of the transects, around 500 m depth and values of fishing intensity ranging from 80 to 2 hauls/ha, depending on the transect. Sardà et al., (2009) and Coll et al., (2010) reported a global tendency of marine organisms to inhabit shallower rather than deeper waters.

However, some classes such as Polychaeta (Annelida phylum) appear to be more likely than others to follow this inclination (Coll et al., 2010). This fact could concur with the findings of this research, which show a preference of these latest phyla (Echinodermata and Annelida) to live in shallower environments rather than in deeper waters. However, it is worth noting that this bathymetric pattern can also be attributable to scarce faunistic investigation on deep waters (Coll et al., 2010).

The large abundance of vertebrates and crustaceans encountered in this study is traceable to the acclimatization capacity of fish and crustaceans, since they can adapt to the deep-sea's stable environment by employing diverse ecological strategies (Sardà et al., 2009). The elevated number of these individuals can also be explained by an increase of scavengers that benefit from organic debris (Kaiser et al., 2000; Hinz et al., 2009). Since they constitute fishing targets, the density of these organisms increases with trawling. Ramirez-Llodra et al., (2009), despite using trawling as a sampling method, also observed a higher proportion of vertebrates and crustaceans relative to the remaining phyla in Blanes Canyon. The low number of other phyla, such as echinoderms encountered on Blanes Canyon was attributed to persistent fishing activities around the area, in accordance to our results, revealing a higher impact and a decline of benthic assemblages with reduced motility.

This fact is supported by the findings of the selective analysis performed for cnidarian individuals. Whereas sessile Anthozoa individuals are mostly found in *Blanes 2* transect (essentially formed by non-impacted soft seafloor), motile scyphozoans are found mostly in the intensively-trawled *Blanes 1*, where the majority of the seafloor was impacted, highlighting the low tolerance of sessile species to the effects of bottom trawling (Clark et al., 2016). This distinction between living areas of the organisms, provides information about the type of seafloor (either impacted, or non-impacted areas) that favours each of the studied classes. Furthermore, it indicates that bottom trawling has the capacity of modifying benthic assemblages of deep-sea environments.

Polychaeta fields were mostly present during the first meters of the transects located in Palamós, at depths ranging from 750 to 500 m, where there was no evidence of rocky outcrop or trawl marks. Although these features and its ecology are largely unknown at present, they might reveal a possible neglected trawled surface.

Indirect impacts of trawling, such as variations on biogeochemical cycling, ought to be contemplated, since alterations of biodiversity, especially of burrowing fauna, can also affect cycling processes of certain biogeochemical compounds. Alternatively, the removal of macro- and meiofauna due to the passage of trawling gear can also modify sediment biogeochemistry (Tiano et al., 2019). These two impacts could modify the overall balance of the ecosystem.

6. Conclusions

The present study provided an assessment of the bottom trawling footprint in Blanes and Palamós canyons, in the Catalan margin. Canyon rims, which are known to shelter a large number of marine organisms, are unceasingly overexploited by fisheries. The economic incentive to increase fish landings, particularly of the valuable deep-sea red shrimp, has triggered a wide expansion of the Catalan coast fishing fleets over the last few years. This case is merely an example of the global trend that the fishing sector has been following during recent years and may continue going forward. More studies focusing on the depth of trawling areas are needed to see if the growth of fishing grounds reflects a deeper expansion of trawlers.

Monitoring systems turn out to be great sources to track fishing activity worldwide; both VMS and AIS are used by vessels all around the world. The comparison of VMS and AIS systems in terms of fishing effort revealed that VMS provide more reliable results than AIS data when studying the spatiotemporal fishing evolution, due to substantial gaps with the latter. Unless additional legislation is promulgated to reinforce the use of AIS and, thereby, increase the coverage of fishing activity, AIS data should not be used as an alternative to VMS data in fishing grounds where fishing fleets tend to turn it off. Studies focused on a more in-depth understanding of both AIS and VMS systems could be developed, especially in cases where AIS data does not reflect properly the actual fishing activity.

The total fishing surface reveals an increasing tendency over the last decade (2008-2018), accompanied by a trend of fishing in deeper waters. Moreover, fishing evolution throughout the year's stations reflects a general pattern, where Winter represents the less fished period. A correlation between fishing intensity and degraded seafloor has been identified, with trawl marks as an effective visual indicator of the physical damage. Yet, further investigation regarding different types of impacts including the sweeping action of trawl nets would be interesting in order to make a more accurate analysis of bottom trawling on the seafloor. Trawled grounds revealed a decrease in faunal abundance and biodiversity, particularly of sessile and reduced-motility species. The low resilience and, thus, the high vulnerability of many deep-sea megabenthic organisms, endures the impacts that this fishing technique may have on local ecosystems. The understanding of the indirect impacts derived from trawling on deep-sea environments and the development of biodiversity indicators may be required to achieve a sustainable and ecosystem-based management.

Attila the Hun postulated, "*There where I have passed the grass will never grow again*", and this statement has accompanied us all along this study. Deep submarine landscapes, one of the most pristine spots of the planet, are starting to be highly modulated by anthropogenic actions. In this way, the present study contributes to the growing understanding of the capacity of this fishing technique to alter these ecological hotspots' original geomorphology and biodiversity. Further investigations and the adaptation of fisheries regulation to the new environmental needs must go hand in hand towards the attempt to foresee and avoid new potentially human footprints in submarine regions.

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Annex

Annex I. Blanes and Palamós fishing fleet

	Vessel	***Enrollment***
1	*Avanza*	*TA-3-2091*
2	*Bonomar F*	*BA-5-3-05*
3	*Ciriaco*	*BA-2-3269*
4	*Estrella del Sur lll.*	*BA-5-1450*
5	*Germans Gras*	*TA-1-1307*
6	*L'Arjau*	*BA-3-3-04*
7	*L'Havanera*	*BA-5-1-92*
8	*La Puntaire*	*BA-3-2591*
9	*Mandorri*	*TA-3-2692*
10	*Montse*	*BA-4-1280*
11	*Nou Gisbert*	*BA-5-1-09*
12	*Noca Gasela*	*BA-5-1-06*
13	*Nuevo Siboney*	*MA-5-862*
14	*Perla de Palamós*	*BA-6-3-04*
15	*Solraig*	*BA-6-5-96*
16	*Tía Cinta*	*CP-2-2098*

Table I.1. The 16 vessels that the BOE regulates. Data acquired from BOE, 2018.

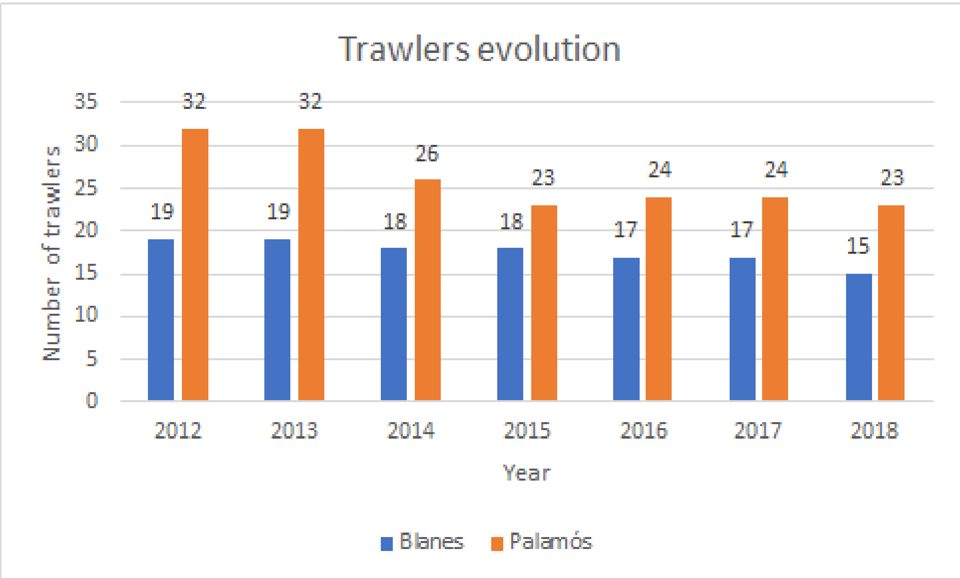

Figure I.1. Blanes and Palamós trawling fleet evolution between 2012 and 2018. Data acquired from Departament d'Agricultura, Ramaderia, Pesca i Alimentació (2020).

Annex II. Banned zones in the study area

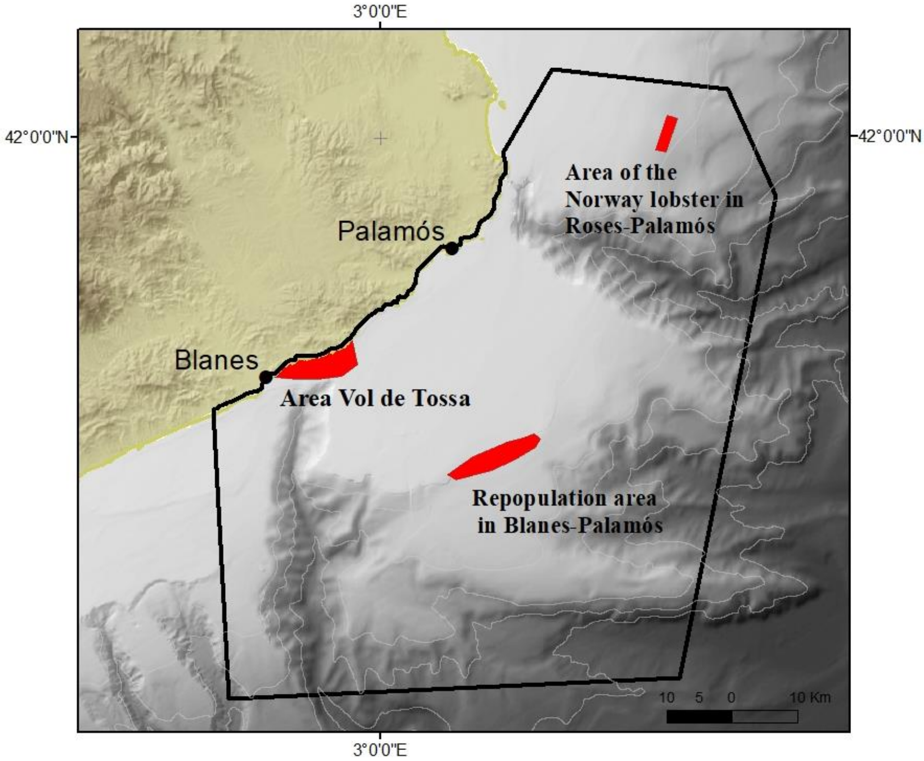

Figure II.1. Banned areas of the study zone. Area Vol de Tossa, Area of the Norway lobster in Roses-Palamós and Repopulation area in Blanes-Palamós. Data acquired from BOE (2012), ICGC and ICM.

Annex III. Fishing grounds in Palamós and Blanes Canyons

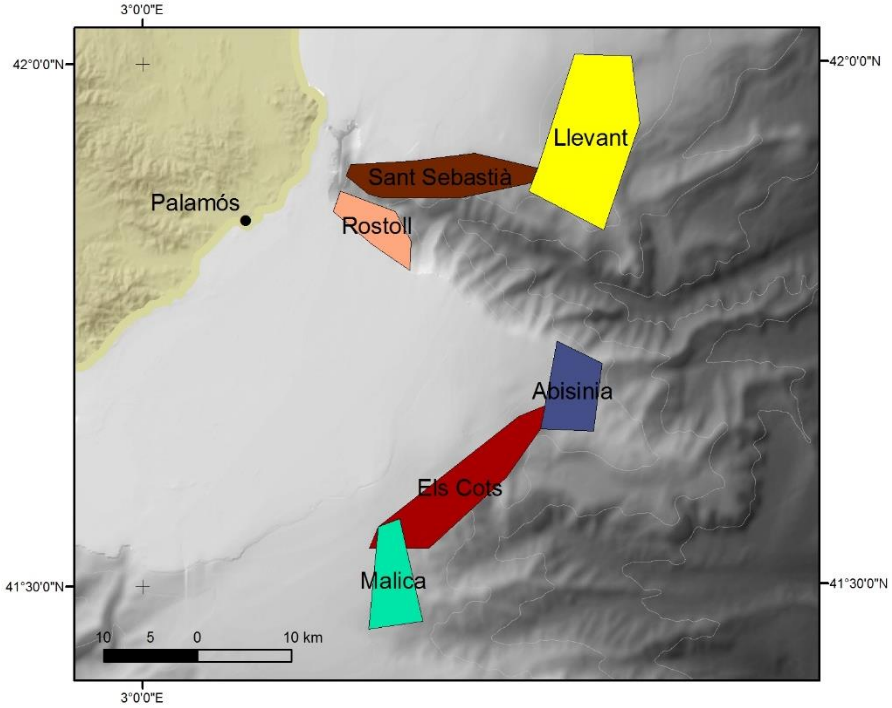

Figure III.1. The six areas regulated by BOE, 2018 that limit the trawling fishery in Palamós coast: El Rostoll, Sant Sebastià, Abisínia, Els Clots, La Malica and Llevant. Data acquired from ICGC and ICM.

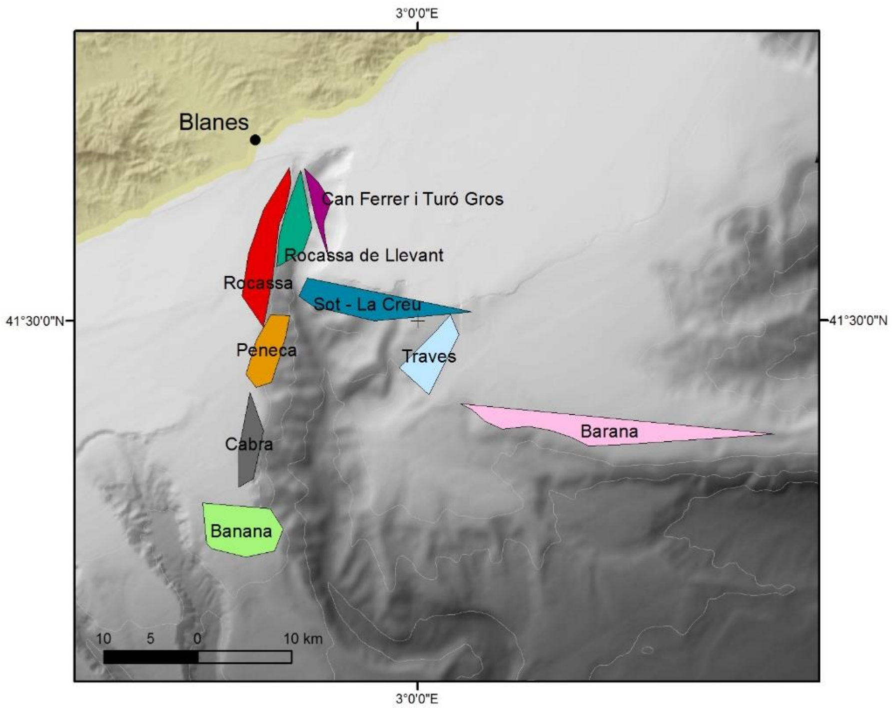

Figure III.2. The eight areas that represent fishing grounds in Blanes Canyon, Barana, Cabra, Can Ferre i Turó Gros, Peneca, Rocassa, Rocassa de Llevant, Sot de la Creu and Travesa. Data acquired from ICGC and ICM.

Annex IV. VMS and AIS data variables

Variable AIS	Value	Description
Nombre	Text	Name of the vessel
Fecha Posición	Numeral	Date of the signal reception
Fecha Posición Mín	Numeral	Specific for each point
Mmsi	Numeral	Marine Mobile Service Identity, unique vessel identifier number
Callsign	Text	Maritime call signs for vessels
Latitud	Numeral	Measured in degrees
Longitud	Numeral	Measured in degrees
Latitud decimal	Numeral	Geographic coordinates (Y)
Longitud decimal	Numeral	Geographic coordinates (X)
Sog	Numeral	Speed Over Ground
Cog	Numeral	Course Over Ground
Heading	Numeral	Direction of the vessel at specific timing
Rot	Numeral	Rotation degree at specific timing
Eslora	Numeral	Size of the vessel
Manga	Numeral	Specific for each point

Variable AIS	Value	Description
Month	Text	Specific for each point
Date	Numeral	Specific for each point
Time	Numeral	Specific for each point
Sog Criteria	Numeral	Specific for each point
Sog Criteria Temp	Numeral	Specific for each point
Trawling	Text	Trawling Activity: True or False
Gear Main	Text	Specific for each vessel
Gear Sec	Text	Specific fro each vessel
Ton Gt	Numeral	Specific for each vessel
Ton other	Numeral	Specific for each vessel
Power Main	Numeral	Specific for each vessel
Power Au	Numeral	Specific for each vessel
Construct	Numeral	Construction year for each vessel
Port	Text	Name of the port
Haul Id	Numeral	Specific for each point

Table IV.1. Variables of AIS data. For each variable, the type of value is distinguished (either text or numeral) and a short description is given. Data acquired from ICM.

Variable VMS	Value	Description
Id	Numeral	A number for each of the points, created by ArcGIS
Code	Numeral	Specific for each vessel
Date	Numeral	Day, month, year and hour of each point
Latitude	Numeral	Geographic coordinates (Y)
Longitud	Numeral	Geographic coordinates (X)
Course	Numeral	Cardinal direction of the vessel
Speed	Numeral	Specific for each point, in knots
Geom	Numeral	Specific for each point
Vessel Id	Numeral	Specific for each vessel
Track Code	Numeral	Specific for all the point of one vessel in a day

Variable VMS	Value	Description
GT	Numeral	Gross tonnage specific for each vessel (Volume measure)
Power Main kW	Numeral	Specific for each vessel
Base Port	Text	Specific for each vessel in a day
Base Port Code	Numeral	Specific for each port
Point Num	Numeral	Number of points in a day for a specific vessel
Ftime point	Numeral	Specific for each point
Kg TOT	Numeral	Kg of landings in one day for a specific vessel
E TOT	Numeral	€ of landings in one day for a specific vessel
LOA m	Numeral	Length overall, specific for each vessel

Table IV.2. Variables of VMS data. For each variable, the type of value is distinguished (either text or numeral) and a short description is given. Data acquired from ICM.

Annex V. Seasonal fishing effort evolution (2008-2018)

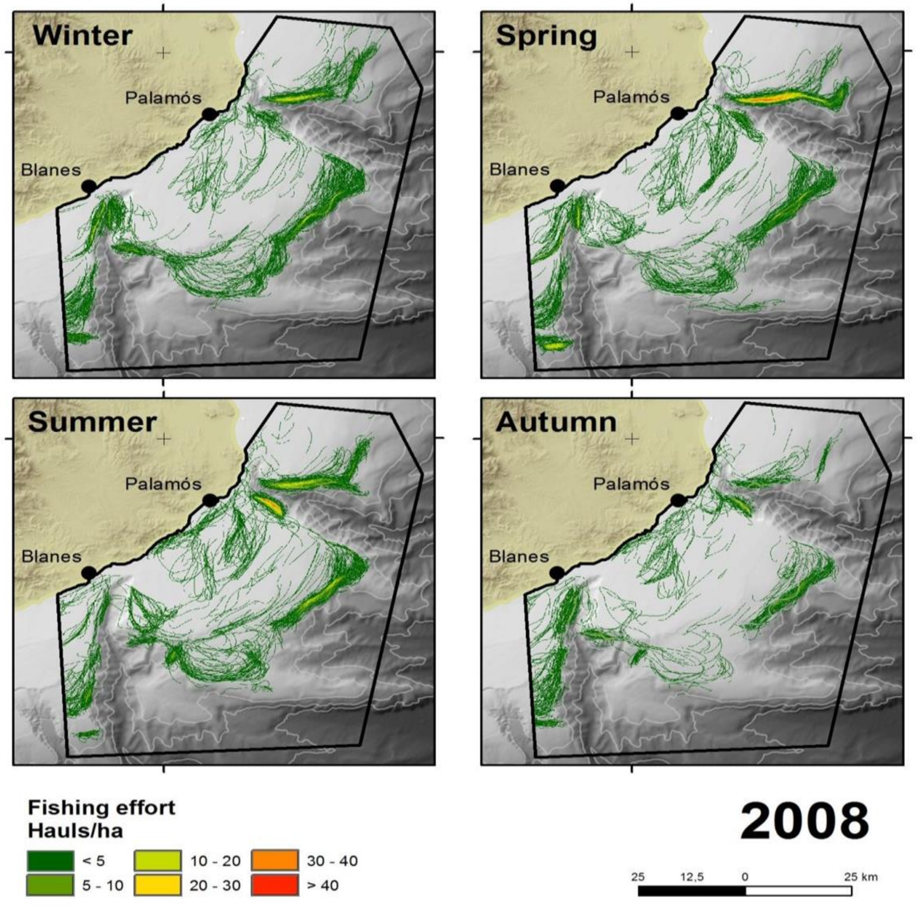

Figure V.1. Seasonal evolution of the fishing effort within 2008. Data acquired from ICGC and ICM.

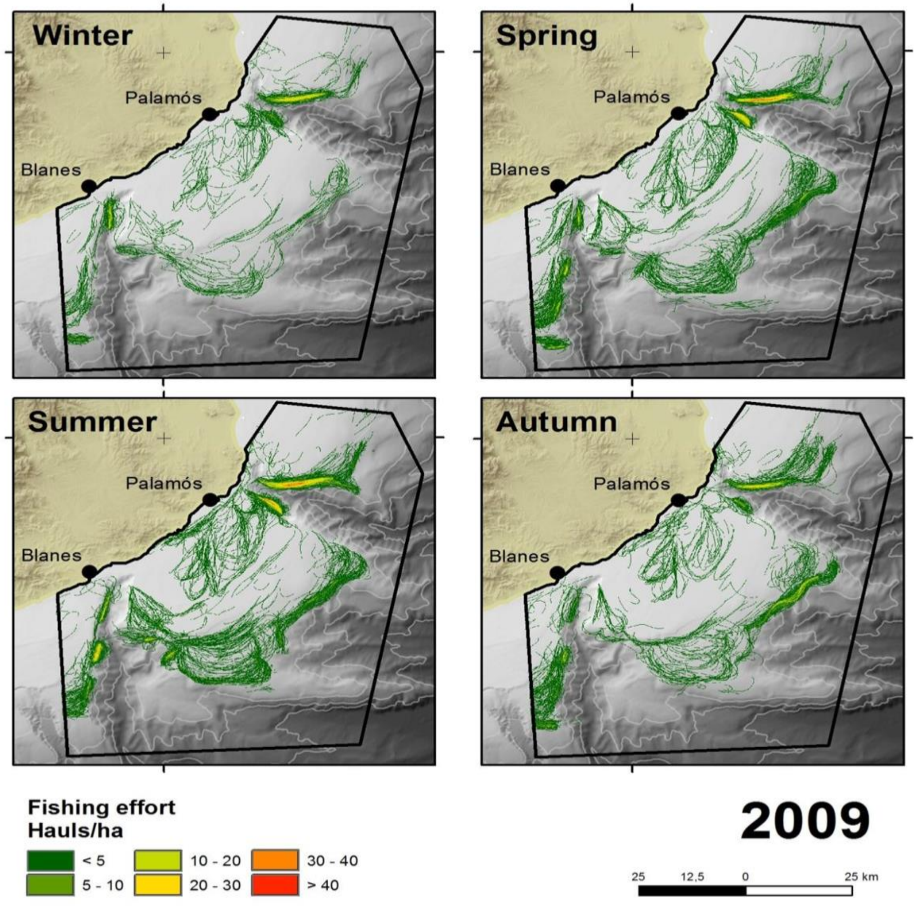

Figure V.2. Seasonal evolution of the fishing effort within 2009. Data acquired from ICGC and ICM.

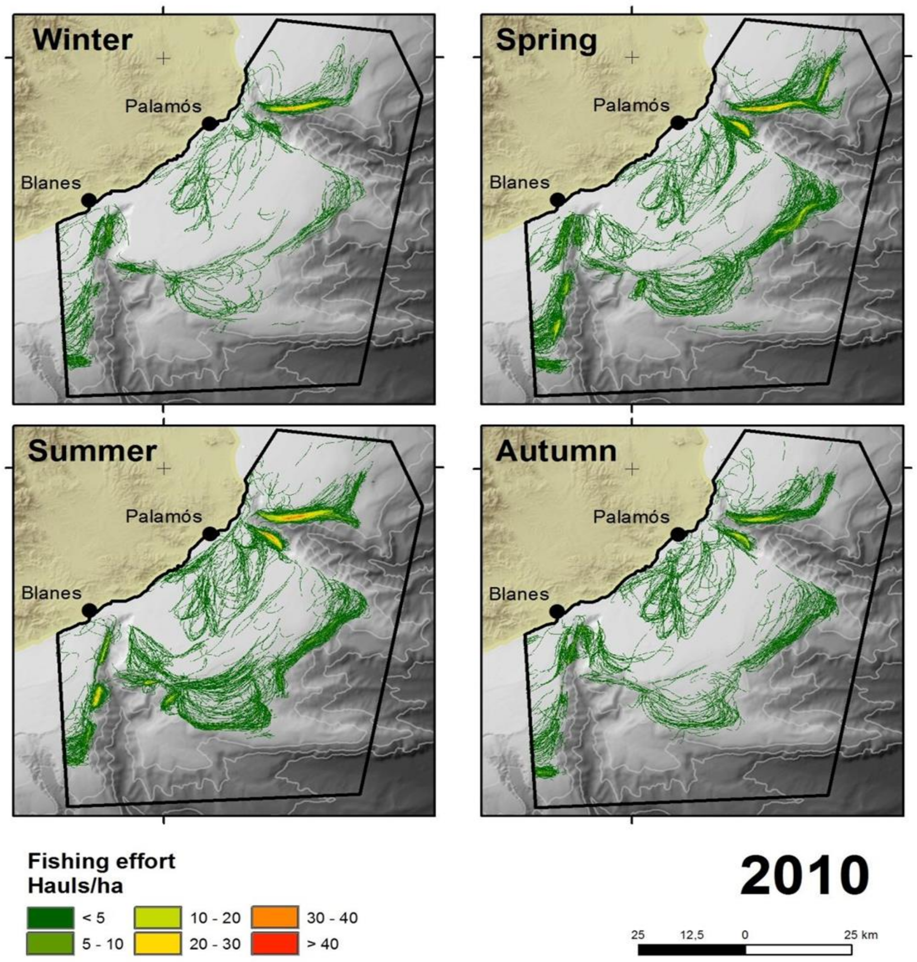

Figure V.3. Seasonal evolution of the fishing effort within 2010. Data acquired from ICGC and ICM.

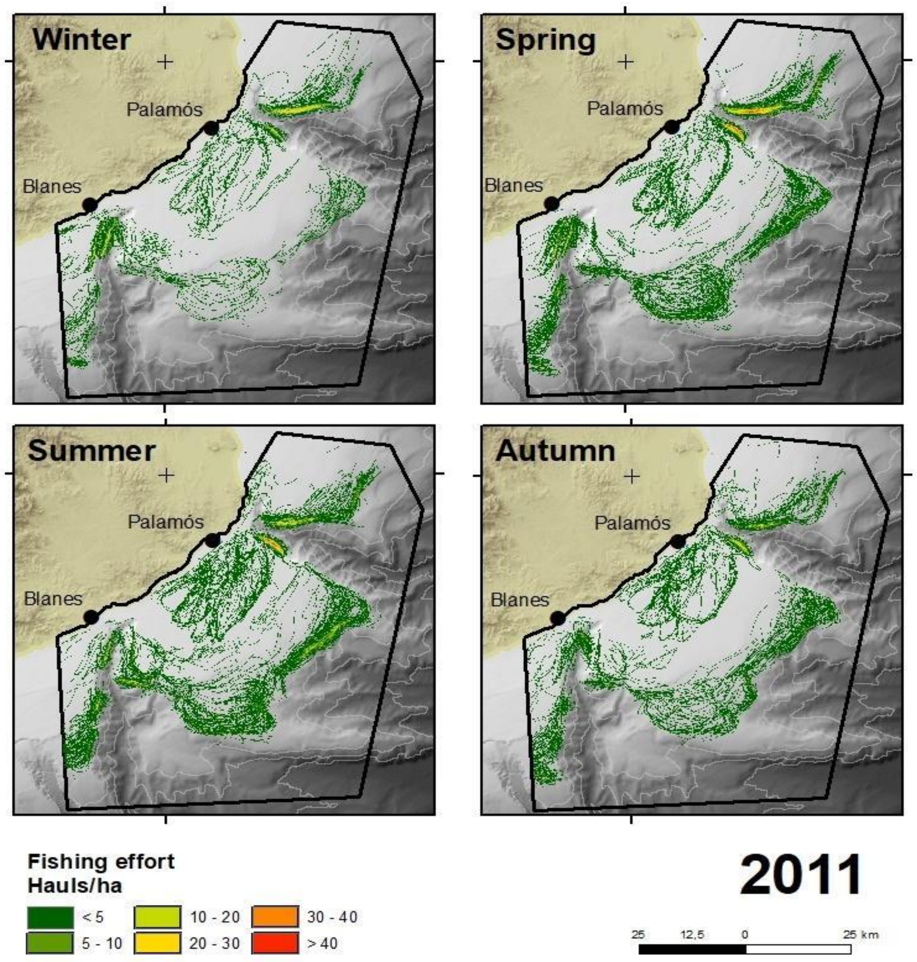

Figure V.4. Seasonal evolution of the fishing effort within 2011. Data acquired from ICGC and ICM.

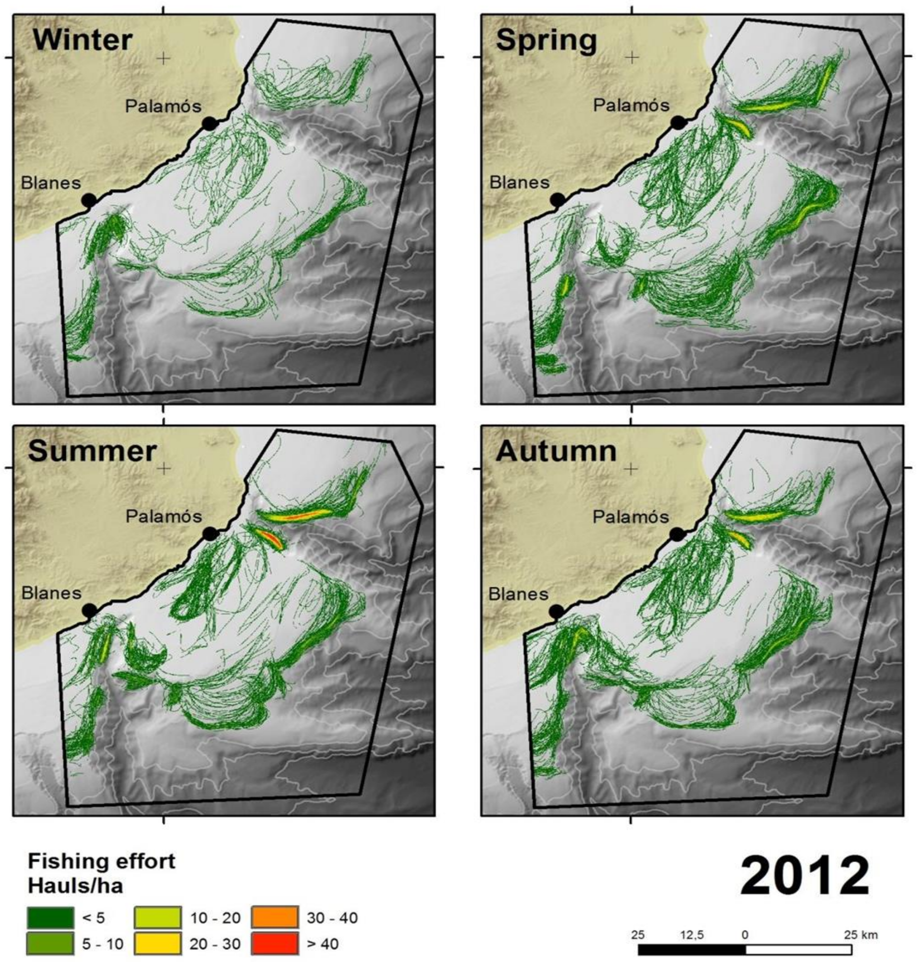

Figure V.5. Seasonal evolution of the fishing effort within 2012. Data acquired from ICGC and ICM.

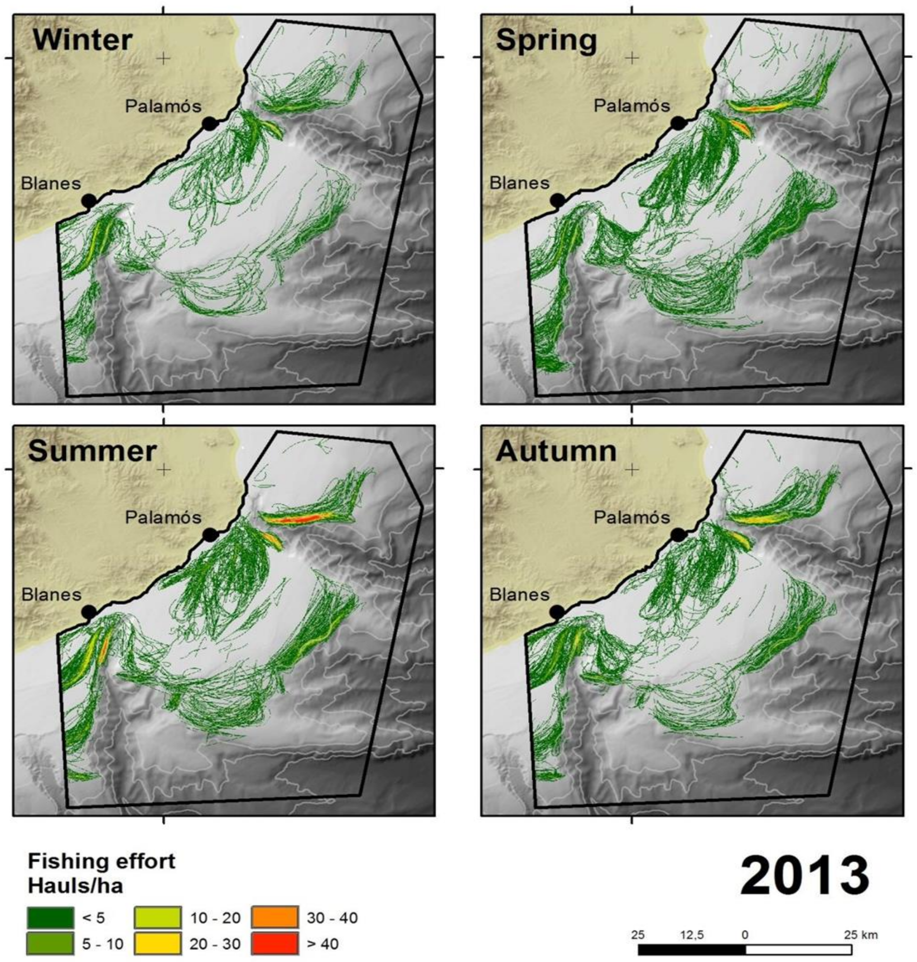

Figure V.6. Seasonal evolution of the fishing effort within 2013. Data acquired from ICGC and ICM.

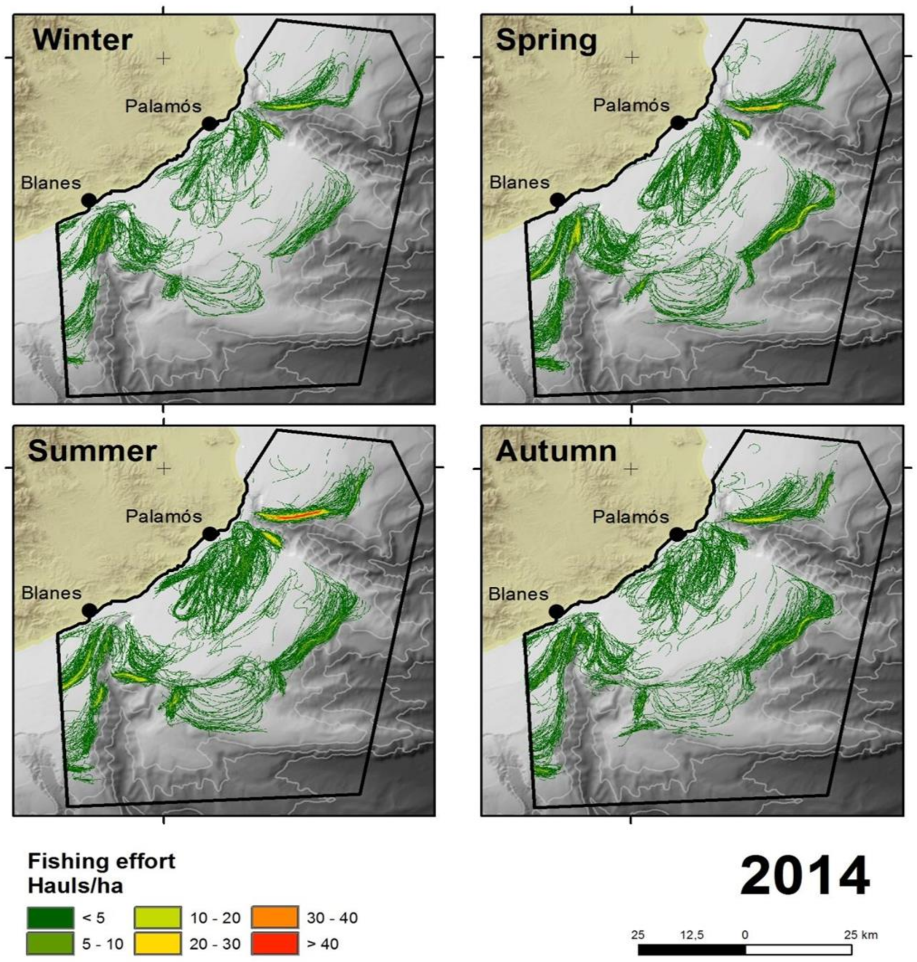

Figure V.7. Seasonal evolution of the fishing effort within 2014. Data acquired from ICGC and ICM.

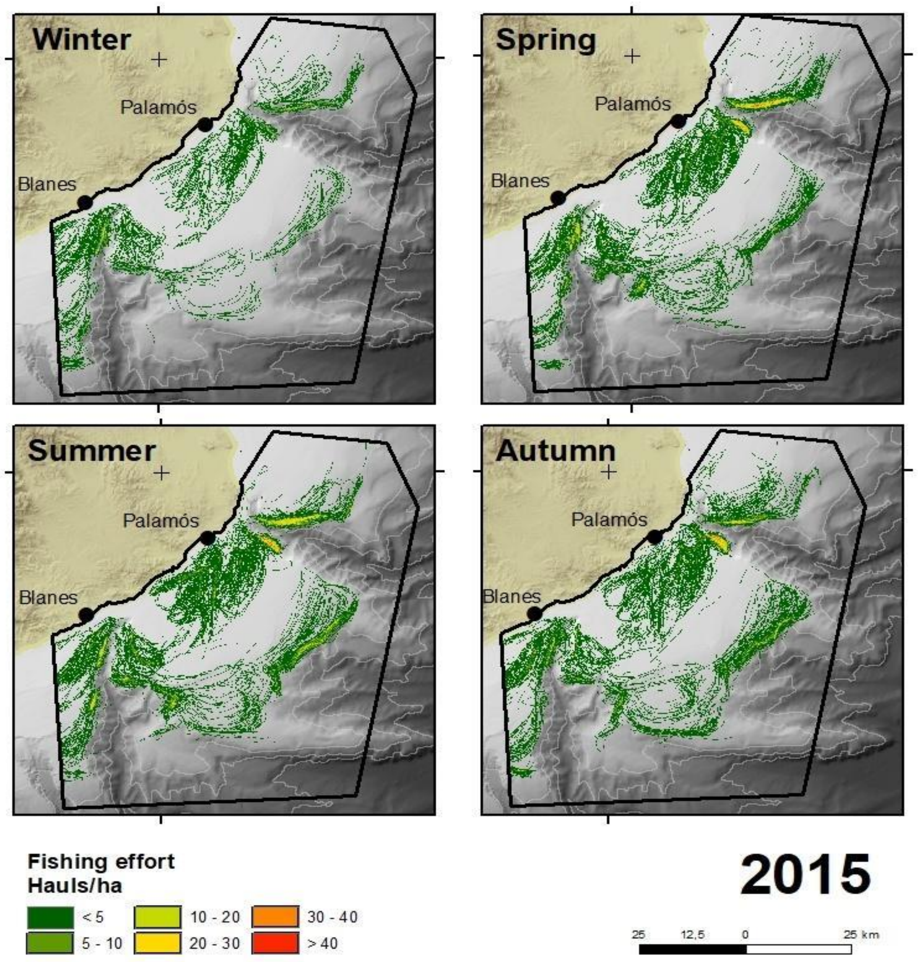

Figure V.8. Seasonal evolution of the fishing effort within 2015. Data acquired from ICGC and ICM.

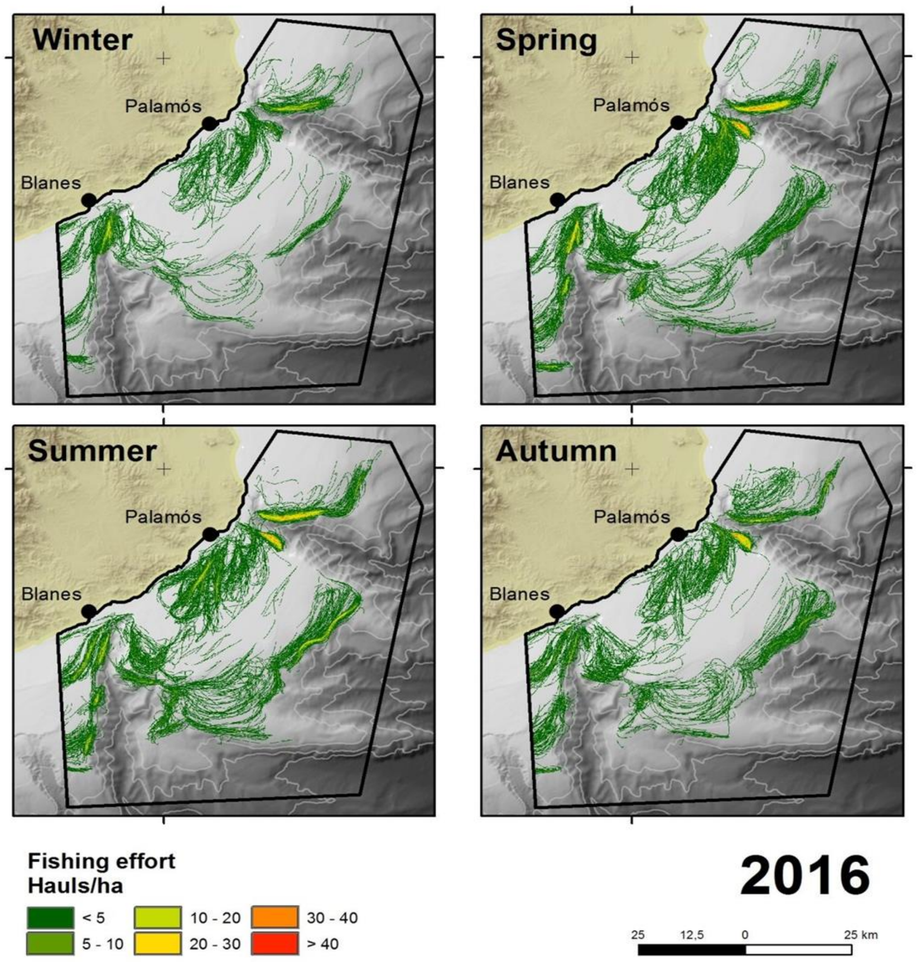

Figure V.9. Seasonal evolution of the fishing effort within 2016. Data acquired from ICGC and ICM.

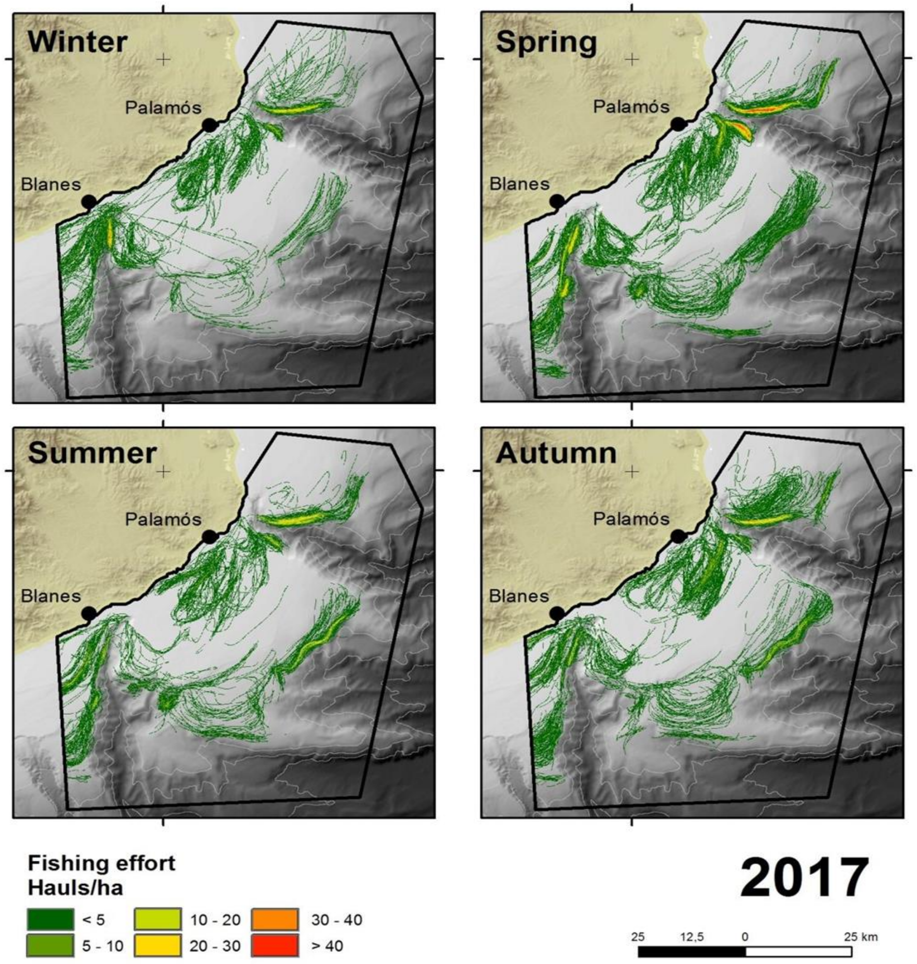

Figure V.10. Seasonal evolution of the fishing effort within 2017. Data acquired from ICGC and ICM.

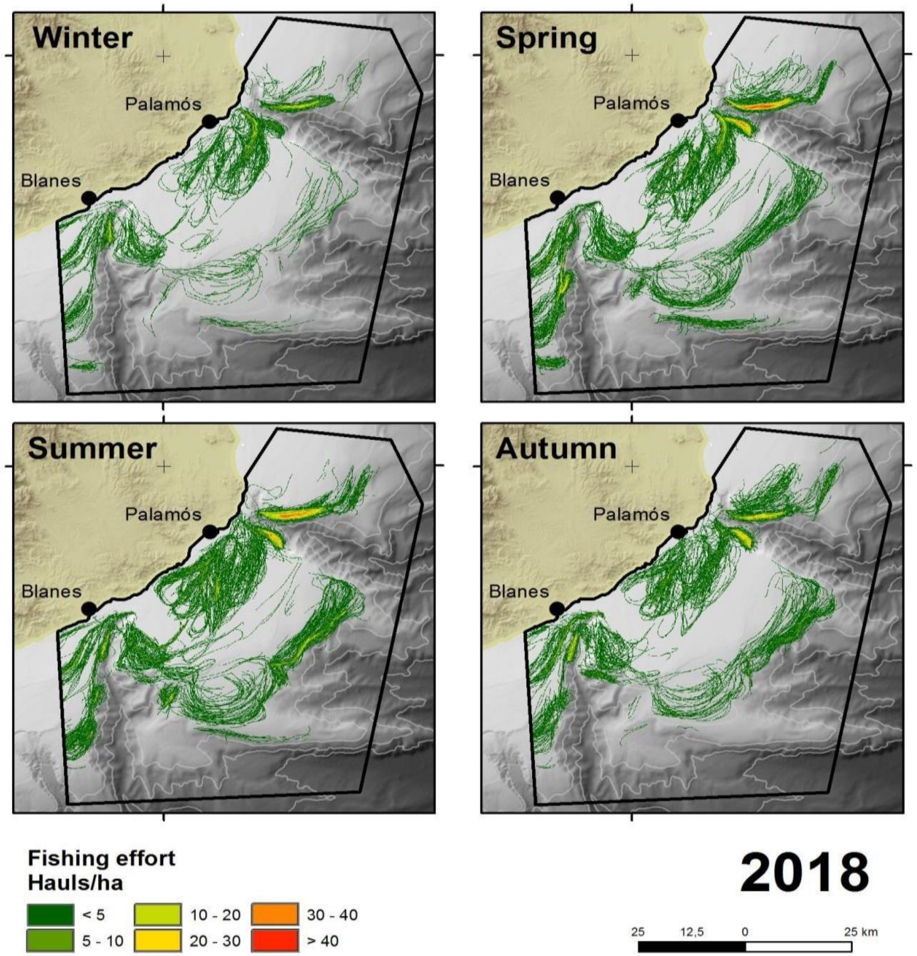

Figure V.11. Seasonal evolution of the fishing effort within 2018. Data acquired from ICGC and ICM.

Annex VI. Schedule of the thesis

	MARCH				**APRIL**				**MAY**				**JUNE**			
Task	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Bibliographic research																
2. Research proposals																
3. Introduction and background																
4. Methodology																
5. VMS and AIS data processing																
6. ROV data processing																
7. Data analysis and interpretation																
8. Discussion																
9. Conclusion																
10. Development of the bachelor thesis																
11. Submition																

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Annex VII. Budget of the thesis

Costs	Description	Unit	Price/unit	Personnel	Total value (€)
Direct costs					
Personnel services	Working hours	490 h	20 €/h	4	39,200.00
	Insurance**	1	5.62 €**	4	22.48
Travels and meetings	Public transport	4 tickets	2.4 €/ticket	4	38.40
Equipment	ROV data acquisition	2 days	200 €/day	1	400.00
	Computers	5 months*	500 €/computer	4	209.00
Total direct costs					39,869.88
Indirect costs					
Total indirect costs (20%)					7,973.98
Total costs					
Total (IVA not included)					47,843.86
Total (21% IVA)					57,891.07

*Considering a 4 years lifetime per computer (500€ priced).

**Considering students' insurance of UAB.

Annex VIII. Carbon footprint

Category						**Emissions (kg CO_2)**
Electricity						
Hours/person	Persons	Computer power (W)	Energy consumption (kWh)		Emission factor (kg CO_2/kWh)	
490,00	3	0.20	294		0.27	79.38
490,00	1	0.20	98		0	0
Total Electricity						79.8
Transport						
Journey	Persons	Journeys	Gt (t)	Distance (km)	Emission factor ($kgCO_2$/km)	
Cerdanyola - ICM	4	2	-	15.40	0.02	2.96
Cerdanyola - UAB	4	4	-	4.00	0.02	1.54
Barcelona - Blanes Canyon	-	2	29,796	73.80	0.13	571,725.65
Barcelona - Palamós Canyon	-	2	29,796	122.50	0.13	949,002.60
Total transport						1,520,732.74
Total emissions						1,520,812.12

** B/O Sarmiento de Gamboa*