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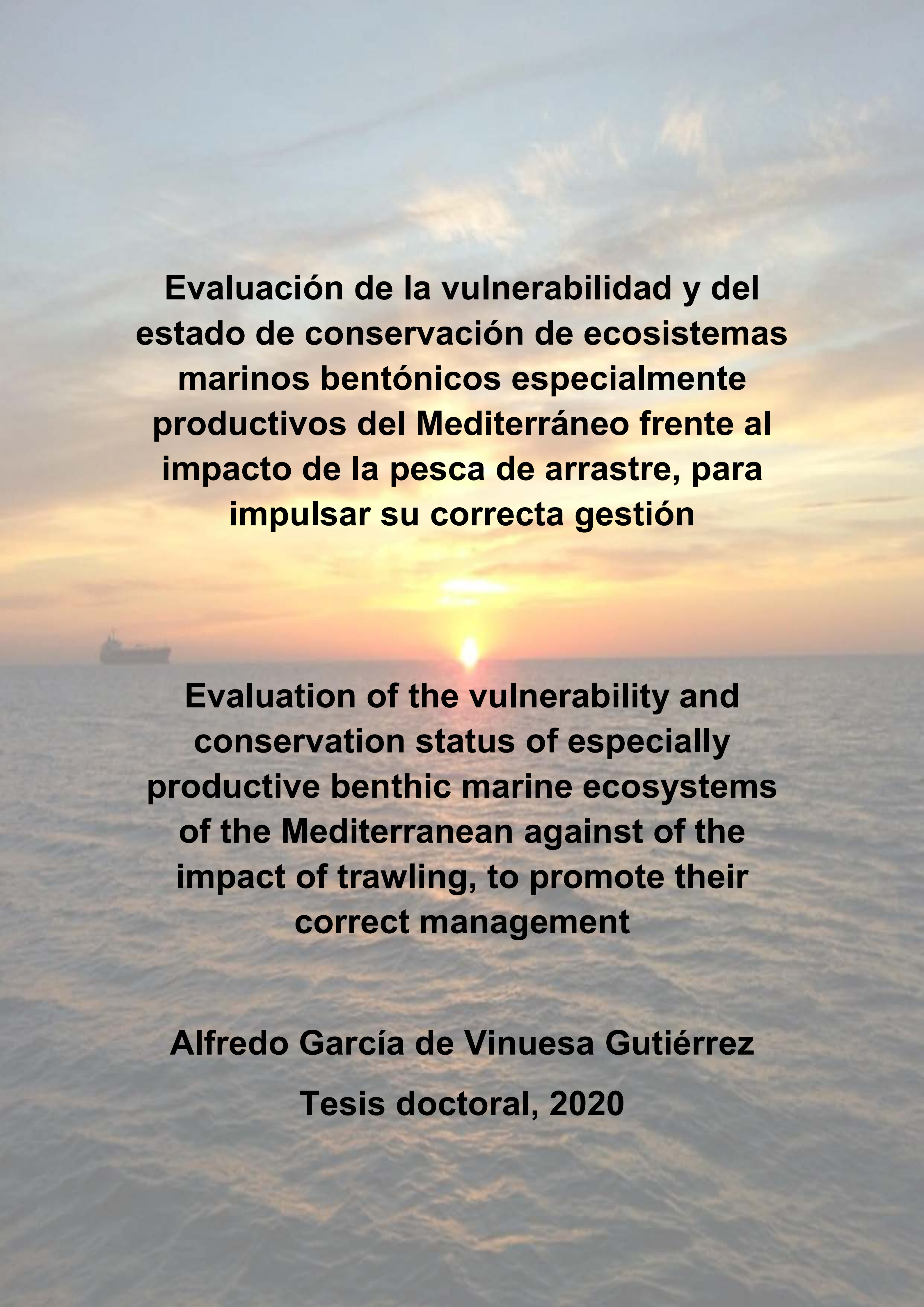

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2020

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Universidad de Barcelona
Facultad de Biología
(Programa de doctorado: ciencias del mar, 2015)
Tesis desarrollada en el departamento de recursos marinos renovables del Instituto de Ciencias del Mar (ICM-CSIC)

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Memoria presentada por Alfredo García de Vinuesa Gutiérrez para optar al título de doctor por la Universidad de Barcelona, bajo la dirección de la Dra. Montserrat Demestre Alted y del Dr. Josep Lloret Romañach

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Octubre, 2020

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AGRADECIMIENTOS

El día que me propuse realizar la primera matrícula esta tesis, fui atendido en la secretaría de la universidad por una persona muy amable que me preguntó en qué tipo de beca me apoyaba para afrontarla. Su cara de incredulidad al explicarle que esta tesis se realizaría sin el apoyo de una beca fue cuanto menos preocupante para mí, a lo que añadió un comentario que auguraba un camino poco halagüeño: “Así que, eres uno de esos pocos valientes que intentan hacer un doctorado sin beca… pues buena suerte muchacho”. Pese a este encontronazo con la realidad de que hay pocas becas para muchas personas que quieren hacer un doctorado, y de que la mayoría de estudiantes desiste al no conseguir una de ellas, tengo que revelar que mi camino hasta la culminación de este trabajo no ha sido ni mucho menos tan difícil como hacía prever, esta por otro lado siempre atenta trabajadora de la secretaría universitaria. La beca institucional que la mayoría de doctorandos poseen, en mi caso ha sido sustituida por el apoyo de personas que han creído en mi trabajo y talento, gracias a las que no me ha faltado apoyo económico, científico ni humano, en ningún tramo de este largo camino. Por este motivo, es totalmente de recibo dar las gracias a dichas personas, sin cuyo apoyo y trabajo no estarías leyendo estas líneas. A Montse Demestre, directora de esta tesis, y eje central de mi aprendizaje desde que llegara a Barcelona recién salido de la Universidad de Cádiz, hace ya la friolera de 10 años. Gracias a su trabajo, grandes dosis de paciencia y trato humano, aparte de ciencia, también he tenido la suerte de aprender acerca de valores en el trabajo y en el trato con las personas. A Josep Lloret, mi otro queridísimo director y sin duda mi benefactor, que ha velado por que no me faltara nada durante el trayecto, y sigue mirando a día de hoy por que encuentre mi sitio en el futuro inmediato. A muchos investigadores del Instituto de Ciencias del Mar (ICM-CSIC), como Francesc Maynou o Pilar Sánchez, que no solo han intervenido dándome también sustento económico durante estos años con sus proyectos, sino que con sus enseñanzas, han colaborado en aumentar la calidad de este trabajo. A todos los compañeros del ICM, que han sacado tiempo de sus propios trabajos para enseñarme técnicas de laboratorio, a entender los ininteligibles programas de estadística o sistemas de georreferenciación, y a identificar un sinfín de especies marinas. A mi familia, por creer en mis proyectos y apoyarme siempre con su tiempo para que yo pueda trabajar en lo que me gusta. Y por último, a todos los pescadores con los que he tenido la suerte de trabajar, muchos de los cuales, cuento hoy como amigos, y que han tenido a bien alojarme en sus maravillosos barcos, gracias a los que he podido acercarme de primera mano todos estos años, a ese mar que tanto quiero.

A todos, Gracias.

RESUMEN

En el mar Mediterráneo existen hábitats especialmente productivos como los fondos de maërl y de agregación de crinoideos, que son explotados en la actualidad por la flota de arrastre. Esta actividad supone un impacto que conlleva la fragmentación física de estos hábitats y provoca una pérdida de diversidad y cambios en la estructura de sus comunidades, afectando de manera directa o indirecta a los estocs de especies comerciales. El enfoque actual de gestión de la pesca de arrastre es ineficaz para corregir la degradación de estos hábitats, ya que está basado fundamentalmente en la biología de las especies objetivo, sin tener en cuenta las comunidades de los propios hábitat. Además, la respuesta de cada hábitat al impacto de la pesca de arrastre es diferente, debido a las diferencias entre comunidades y a las particularidades físicas de cada hábitat. Esta tesis centró sus esfuerzos en el estudio de hábitats de maërl y de crinoideos explotados por la pesca de arrastre, buscando su localización, cuantificando el impacto al que son sometidos, evaluando indicadores novedosos que ayuden a determinar su estado de conservación y su vulnerabilidad ante dicha pesca, y comparándolos con fondos fangosos, en general más conocidos y estudiados. Los indicadores utilizados fueron: (i) la supervivencia de invertebrados al descarte de la pesca de arrastre, (ii) la vulnerabilidad a la pesca de arrastre de las comunidades de infauna y (iii) los ácidos grasos de salmonetes (*Mullus spp*.) y sus presas.

Los resultados de esta tesis, muestran una alta supervivencia para especies de invertebrados como *Leptometra phalangium* y *Antedon mediterránea,* típicas de los hábitats de crinoideos, o para especies objetivo de la pesca de arrastre en los fondos de fango, como la cigala (*Nephrops norvegicus),* cuya supervivencia mostró una acusada estacionalidad, siendo alta durante los meses de invierno y muy baja durante los meses de verano. Se encontraron importantes diferencias en la vulnerabilidad a la pesca de arrastre de la comunidad de infauna de hábitats de maërl respecto a la de fondos fangosos. También se demostró que la composición lipídica de salmonetes e infauna en hábitats de maërl es diferente a la de los salmonetes e infauna de fondos de fango, y que esta composición se puede relacionar con la pesca de arrastre.

Basándonos en los resultados obtenidos, se proponen medidas de gestión que promuevan el equilibrio entre explotación y conservación, atendiendo a las particularidades de cada hábitat, como: a) implementación de mejoras técnicas que aumenten la supervivencia del descarte, b) creación de áreas marinas protegidas (AMPs) sobre hábitats de maërl, o c) ampliación de vedas temporales en hábitats de agregación de crinoideos.

ABSTRACT

In the Mediterranean Sea, there are especially productive habitats such as maërl and crinoid aggregation bottoms that are currently exploited by the trawl fleet. This activity has a high impact that entails the physical fragmentation of these habitats and it causes loss of diversity and changes in the structure of their communities, directly or indirectly affecting the stocks of commercial species. The current approach to trawling management is ineffective in correcting the degradation of these habitats, as it is fundamentally based on the biology of the target species, without taking into account the communities of the habitats themselves. Furthermore, the response of each habitat to the impact of trawling is different, due to their differences between communities, and their physical peculiarities. This thesis focused its efforts on the study of maërl and crinoid habitats exploited by trawling, seeking their location, quantifying the impact to which they are subjected, evaluating innovative indicators that help determine their conservation status and vulnerability to trawling, and comparing them with muddy bottoms, generally better known and studied. The indicators used were: (i) the survival of invertebrates when discarded by trawling, (ii) the vulnerability to trawling of the infauna communities and (iii) the fatty acids of red mullets (*Mullus spp*.) and their prey.

The results of this thesis, show a high survival rate for invertebrate species such as *Leptometra phalangium* and *Antedon mediterranea* (typical species of the crinoid habitats) or for trawling target species of the mud bottoms, such as Norway lobster (*Nephrops norvegicus*), whose survival showed a marked seasonality, being high during the winter months and very low during the summer months. Important differences were found in the vulnerability to trawling of the infauna community in maërl habitats compared to that of muddy bottoms. It was also shown that the lipid composition of red mullet and infauna in maërl habitats is different from that of red mullet e infauna of mud bottoms, and that this composition can be related to trawling.

Based on the results obtained, several management measures are proposed to promote a better balance between exploitation and conservation, taking into account the particularities of each habitat, such as: a) implementation of technical improvements that increase the discard survival, b) creation of marine protected areas (MPAs) on maërl habitats, or c) extension of temporary closures in crinoid aggregation habitats.

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Introducción general

1. La pesca de arrastre en el mar Mediterráneo

a) El hombre en el mar Mediterráneo y la polémica pesca de arrastre

Los variados e intensivos usos que se le han dado al mar Mediterráneo desde hace milenios, han hecho que el impacto de las actividades humanas sea proporcionalmente más fuerte en este mar, que en cualquier otro mar del mundo, por lo que hoy en día no podríamos comprender el Mediterráneo sin atender a su relación con el hombre (Margalef 1985; Bas 2005; Coll et al., 2010; Blondel et al., 2010). En la actualidad, los bienes y servicios que ofrece el Mediterráneo van desde la extracción de recursos vivos y energéticos (Depellegrin et al., 2019), hasta los beneficios físicos y psicológicos que proporcionan las actividades recreativas en la costa y en el mar (Bowen y Halborson 1996; Sofi et al., 2008; Lloret 2010). Además, anualmente las costas mediterráneas atraen a unos 200 millones de turistas, que representan un pilar básico de la economía de los países ribereños (Goffredo y Dubinsky 2013). Pero sin lugar a duda, la actividad que históricamente ha relacionado más estrechamente al ser humano con el mar Mediterráneo ha sido la pesca, de cuya práctica ya dejaron constancia hace milenios fenicios y romanos (Zamora 2004; Busana 2018). Desde entonces, la pesca ha tenido importancia no solo como parte fundamental de la economía de las poblaciones costeras, sino también como parte intrínseca de su cultura, manteniendo el tejido social de las comunidades (FAO 2018). Sin embargo, hoy en día la pesca está considerada una de las actividades humanas más nocivas para los océanos (Jackson et al., 2001), por lo que de la habilidad de los países mediterráneos para gestionar su impacto en el medio marino, dependerá en gran medida que este mar siga siendo fuente de riqueza para los habitantes de sus costas.

Actualmente, coexisten en el Mediterráneo multitud de modalidades pesqueras que van desde modalidades recreativas como la pesca submarina o la pesca con caña, hasta modalidades profesionales como la pesca artesanal, la pesca de arrastre y la pesca de cerco. Pese a representar un menor porcentaje en cuanto a número de embarcaciones que la flota artesanal, tanto la flota de arrastre como la de cerco tienen mayor potencia y tamaño, por lo que descargan cantidades de captura mucho mayores (Lleonart et al., 1998; Lloret et al., 2008; Spagnolo 2012). De estas dos, la pesca de arrastre es la que mayor problemática medioambiental presenta (Sommer 2005). Por este motivo, esta tesis direcciona sus esfuerzos concretamente hacia el estudio del impacto de la pesca de arrastre sobre los hábitats mediterráneos.

La pesca de arrastre, llegó a aguas mediterráneas entre finales del siglo XVII y principios del XVIII, según un escrito de Joan Salvador i Riera que data de 1722. Más específicamente comienza a practicarse en los mares de Cataluña, Provenza y Liguria y rápidamente se extiende a Valencia para expandirse más tarde al resto de la península ibérica (Lleonart et al., 1990).

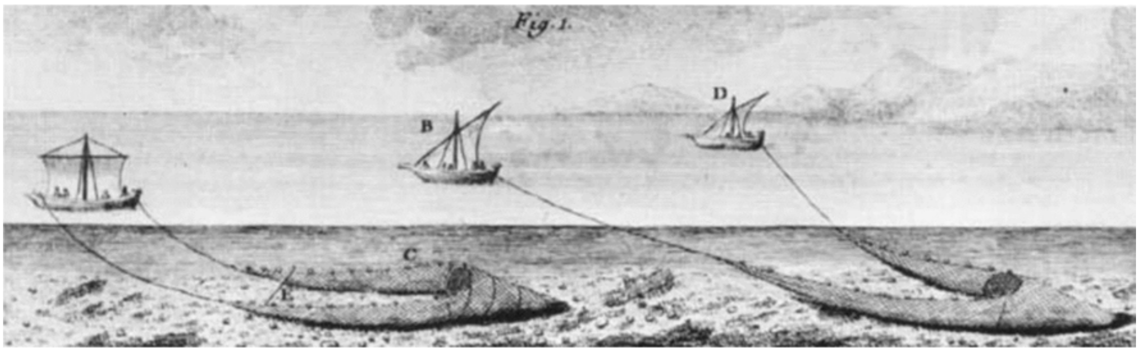


Fig 1.- Primeras modalidades de pesca de arrastre introducidas en el Mediterráneo, según Duhamel du Monceau. Se puede observar la modalidad del ganguil a la izquierda (pesca con una sola barca a vela) y la de bou a la derecha (pesca a vela en parejas). Extraído de Lleonart y Camarasa 1987.

Desde su comienzo, la pesca de arrastre ha sido motivo de polémica y enfrentamiento entre pescadores. En este sentido, se conservan escritos como el de Tomás Güell prohibiendo la pesca de arrastre en Valencia en 1736, y otros de la década de 1750, donde los pescadores de modalidades pesqueras artesanales valencianos, se quejaban de la explotación indiscriminada que el arrastre hacía de los recursos, por lo que la implantación de medidas restrictivas para la pesca de arrastre, existe casi desde su llegada a la península ibérica (Lleonart y Camarasa 1987; Viruela 1993). Durante todo el siglo XIX siguieron sucediéndose las protestas e intentos de regulación del arrastre y con la llegada del motor a principios del siglo XX, el desembarco de capturas, tanto para el arrastre como para las demás modalidades pesqueras, comenzó un exponencial ascenso, hasta que en la década de los 90 tocó techo (Pontecorvo y Schrank 2014). Desde entonces, las capturas en el Mediterráneo van en descenso, y se considera que la gran mayoría de las poblaciones estudiadas, (78 %) están sobreexplotadas, lo que significa que se están capturando más individuos de los que la población es capaz de reponer de forma natural (FAO 2018). Hoy en día, la pesca de arrastre sigue siendo motivo de polémica, y su gestión es aún un quebradero de cabeza para los pescadores, los científicos y las administraciones.

Figura 2.- Pequeña barca de arrastre del Mediterráneo, utilizada durante los muestreos de esta tesis en la plataforma continental.

b) Impactos de la pesca de arrastre

Actualmente, la pesca de arrastre está considerada la actividad antropogénica con mayores efectos negativos sobre los fondos marinos (Jennings y Kaiser 1998; Sommer 2005), porque destruye, fragmenta y homogeniza los ecosistemas bentónicos, disminuyendo consecuentemente la abundancia y diversidad de las especies que los habitan (Kayser et al., 2000; Thrus y Dayton 2002; Demestre et al., 2008). De esta manera, también afecta directa o indirectamente a la condición de las especies comerciales que ven disminuidos sus stocks, disminuyendo así la provisión de bienes y servicios ecosistémicos (Lloret et al., 2007; Muntadas et al., 2015). Para entender este despropósito ecológico, hay que atender a la propia naturaleza de esta pesca. La pesca de arrastre basa su actividad en remolcar una red con una relinga de plomos en su parte inferior, que se arrastra por el fondo marino, cuya abertura horizontal se consigue por la hidrodinámica de dos divergentes metálicos, llamados popularmente “puertas”, que pueden pesar desde cientos de quilos hasta toneladas. La parte superior de la red consta de una relinga de con flotadores con la que se consigue la abertura vertical de la red mientras se arrastra. Así, este arte pesquero captura casi todos los organismos que se hallan sobre la superficie o enterrados en los primeros centímetros del sedimento (Thrush et al., 1998; Mangano et al., 2014, Cyrielle et al., 2020), siendo la multiespecificidad una de sus características más marcadas. Por este motivo, esta pesca de fondo es también la menos selectiva que existe, en la que muchas de las especies capturadas carecen de valor comercial, por lo que son devueltas al mar. Esto es lo que se conoce como el descarte, el cual en el Mediterráneo puede suponer más del 40% del peso de la captura (Tsagarakis et al., 2014, 2017). Gran parte de los animales que componen este descarte, son devueltos al mar dañados o muertos debido al impacto de la propia pesca y la manipulación de la captura a bordo (García-de-Vinuesa 2012; Tsagarakis et al., 2018; Mérillet et al., 2018). Entre estos animales se incluyen desde individuos inmaduros de especies comerciales, es decir, que no han alcanzado la talla o edad de madurez sexual (Jennings y Kaiser 1998; Bellido et al., 2017), hasta invertebrados no comerciales, que juegan un papel importante en la funcionalidad de los ecosistemas (Lohrer et al., 2004; Demestre et al., 2008; de Juan et al., 2011). La problemática medioambiental generada por la pesca de arrastre es importante, pero la pesca en sí, es un pilar económico y cultural en el Mediterraneo. Por lo tanto, es necesario conseguir un tipo de gestión que establezca un equilibrio entre la explotación de los recursos y la conservación de los ecosistemas, para que de esta manera, la pesca pueda seguir generando riqueza y formando parte de la cultura de las poblaciones mediterráneas.

Figura 3.- Captura de una barca de arrastre, en la que se puede observar la multiespecifidad del arte y gran cantidad de especies que serán descartadas, como el crinoideo *Leptometra phalangium.*

2. Ecosistemas altamente productivos del mar Mediterráneo afectados por la pesca de arrastre

A pesar de sus dimensiones, en relación con otros mares y océanos, el mar Mediterráneo es un punto caliente ("hot spot") en cuanto a biodiversidad, ya que en sus aguas cohabitan aproximadamente 17000 especies marinas de las que alrededor de un 28% son endémicas, lo que hace del mar Mediterráneo una de las áreas prioritarias de conservación a nivel global (Tortonese 1985; Bianchi 2007; Coll et al., 2010). Esta diversidad es fundamental para el correcto funcionamiento de los ecosistemas Mediterráneos, siendo uno de los elementos que define la capacidad de resiliencia de los ecosistemas ante un estresor natural o antropogénico (Muntadas et al., 2015). Además, está directamente relacionada con su productividad (de Juan y Hewitt 2014; Lohrer et al., 2004). La distribución de la diversidad marina en el Mediterráneo es muy heterogénea, encontrándose en mayor grado en ecosistemas de la plataforma continental de la cuenca occidental, ya que ésta es más ancha, y por sus características físico-químicas tiene la capacidad de albergar algunos de los ecosistemas marinos más diversos del mundo (Coll et al., 2010). Precisamente, es sobre la plataforma continental donde se desarrolla la mayoría de la actividad de la flota de arrastre (Thrus y Dayton 2002).

Algunos de los ecosistemas más productivos del Mediterráneo son los fondos de maërl, los fondos de agregaciones de crinoideos y ciertas áreas de los fondos fangosos (Gray 2002; Massi et al., 2016; Basso et al., 2017). Todos ellos, son hábitats fundamentales para que especies comerciales se alimenten, desoven o crezcan hasta la madurez, lo que se conoce como hábitats esenciales para peces (en inglés EFH, de "Essential Fish Habitats") (Auster y Langton 1998). Por este motivo, mantenerlos en un buen estado de conservación es fundamental para conseguir un buen estado funcional de los bienes y servicios que, en forma de especies comerciales, ofrecen estos hábitats. Los EFH más costeros, como los de *Posidonia oceánica*, están protegidos de la pesca de arrastre debido a la prohibición de ésta a menos de 50 metros de profundidad (EU Reg. 1967/2006). Sin embargo, ciertas áreas de los hábitats de maërl, de los fondos de fango y todos los hábitats de agreación de crinoideos, se encuentran a profundidades mayores, y son explotados por la flota de arrastre en el Mediterráneo (Snelgrove et al., 2014; Massi et al., 2016; Demestre et al., 2017), por lo que su integridad ecológica se encuentra en peligro. La localización de estos EFH, su caracterización, y la evaluación de los impactos a los que se ven sometidos, es fundamental para poder gestionarlos de manera adecuada, por lo que esa tarea se planteó como primer objetivo, y ha sido desarrollada en el capítulo 1 de esta tesis.

a) Habitats de maërl

Los hábitats de maërl se distribuyen a través del todo el mar Mediterráneo, pueden encontrarse desde los 9 hasta los 150 metros de profundidad, pero su abundancia aumenta alrededor los 55 metros de profundidad (Basso et al., 2017). Están formados por acumulaciones de varias especies de algas rojas calcáreas que pueden formar estructuras conocidas como rodolitos (Ramos-Espla y Luque 2008). Estas formaciones calcáreas, proporcionan una configuración tridimensional al fondo marino, que sirve de refugio a multitud de pequeños invertebrados que conforman la dieta de importantes especies comerciales como el salmonete de roca (*Mullus surmuletus*), que encuentra en este EFH una perfecta zona para su reproducción y crecimiento juvenil (Barberá el al., 2003; Muntadas et al., 2015). Debido a su lento crecimiento, los fondos de maërl están considerados un hábitat vulnerable del Mediterráneo, y existe una enorme falta de información acerca de su localización y de sus niveles de conservación (Basso et al., 2017; Demestre et al., 2017). Las medidas de gestión actuales adoptadas para preservarlos, ni se cumplen por los usuarios, ni se hacen cumplir por los gestores, ya que pese a existir una prohibición expresa para la pesca de arrastre en estos fondos (EU Council Regulation 1967/2006), y estar incluidos, tanto el propio hábitat como dos de las principales especies del maërl (*Lithothamnium corallioides* y *Phymatolithon calcareum*), en el Anexo I y el Anexo V de la Directiva Hábitat de la Unión Europea respectivamente, siguen siendo explotados por la flota de arrastre en el Mediterráneo (Barbera et al., 2003; Ramos-Espla y Luque 2008; Ordines et al., 2017).

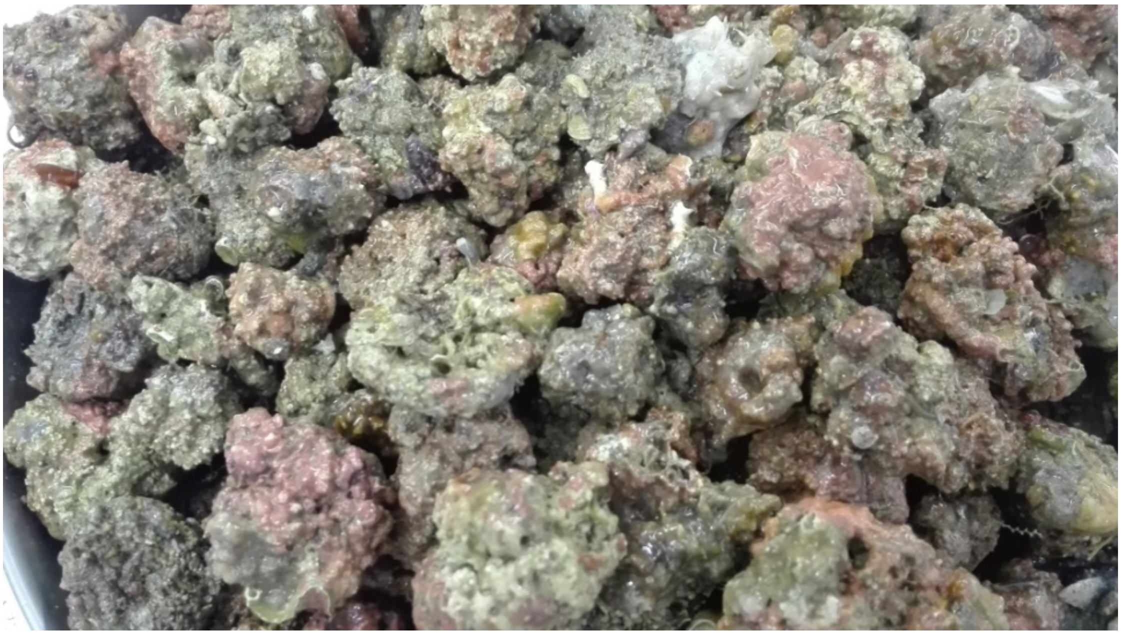


Figura 4.- Rodolitos de un hábitat de maërl, situado en el área de estudio de esta tesis.

b) Hábitats de agregación de crinoideos

Los hábitats de agregación de crinoideos están distribuidos a lo largo del mar Mediterráneo, en zonas situadas entre el borde de la plataforma continental y el inicio del talud (entre los 120 y 170 metros de profundidad), caracterizadas por presentar una gran abundancia del crinoideo (equinodermo) *Leptometra phalangium* y en menor medida del crinoideo *Antedon mediterranea* (Colloca et al., 2004; Leonard et al., 2020). Esta zona de transición, entre el final de la plataforma continental y el inicio del talud, es una zona de alta energía, donde se producen importantes fenómenos de mezclas de agua que se traducen en un enriquecimiento de nutrientes y aumento de la producción primaria (Vanney y Stanley 1983; Mann y Lazier 1996). Aquí, los crinoideos encuentran un sitio perfecto para alimentarse, fijando nutrientes al bentos y sirviendo de base para la constitución de un EFH para varias especies de alto valor comercial, como la merluza (*Merluccius merluccius*) o el rape (*Lophius spp*), que los utilizan como zona de alevinaje (Colloca et al., 2009; Massi et al., 2016). Son considerados hábitats sensibles del Mediterráneo (STEFC 2006) y están reconocidos por la Unión Europea como hábitats esenciales para la pesca (European Commission 2006). Pese a ello, a día de hoy también siguen siendo frecuentados por las flotas de arrastre del Mediterráneo (Porporato et al., 2010; Mallol 2012; Massi et al., 2016).

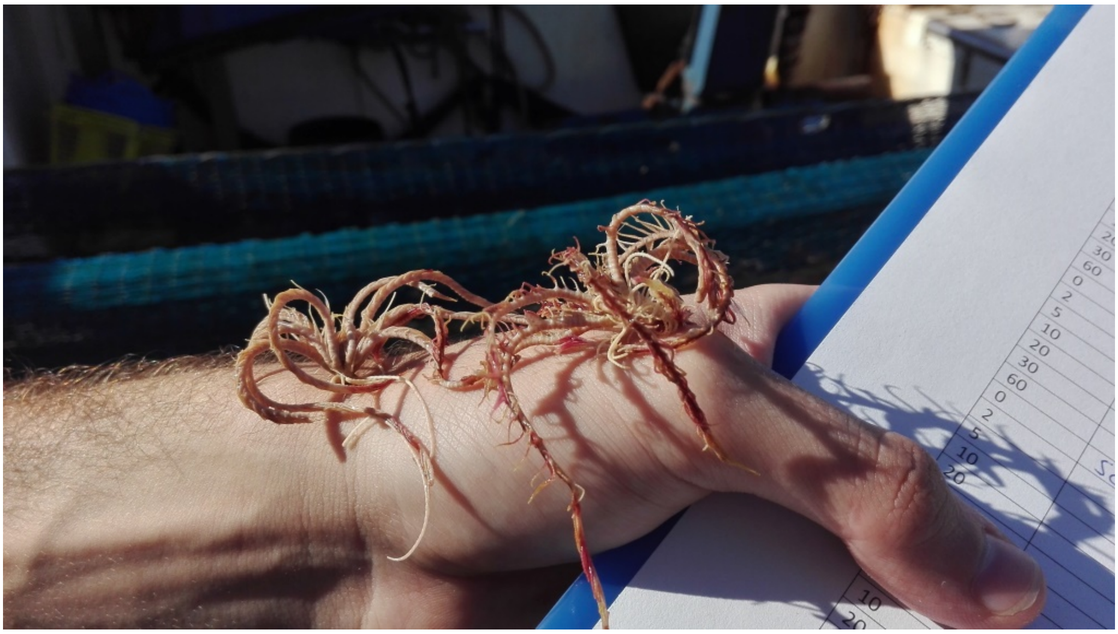


Figura 5.- Crinoideos del área de estudio de Blanes. *Leptometra phalangium* (izquierda), *Antedon mediterranea* (derecha)

c) Los fondos fangosos

Los fondos fangosos tienen una enorme extensión, no solo en el mar Mediterráneo, sino a nivel global (Snelgrove et al., 1999), y una amplia distribución batimétrica, desde zonas muy someras hasta miles de metros bajo la superficie oceánica. En algunas zonas, pueden albergar una alta diversidad de especies y sostener importantes comunidades bentónicas que proporcionan servicios ecosistémicos fundamentales (Coleman et al., 1997; Gray 2002; Thrush y Dayton 2002). Ademas, al igual que los hábitats de maërl y de agregacion de crinoideos, determinadas zonas los fondos de fango, funcionan como EFH para juveniles de algunas especies comerciales, como el salmonete de fango (*Mullus barbatus*), la gamba blanca (*Parapenaeus longirostris*) o la cigala *(Nephrops norvegicus*), donde junto a otras especies comerciales, como el pulpo (*Eledone cirrhosa*), La merluza o el rape, son explotadas debido a su alto valor comercial.

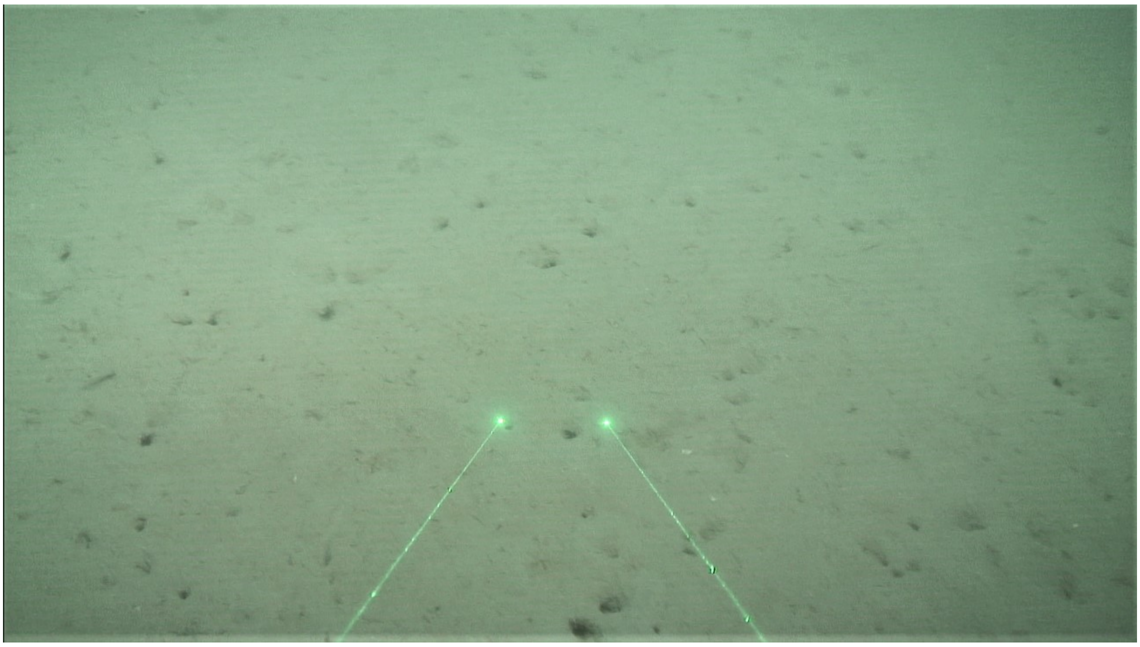


Figura 6.- Fondo de fango localizado con el ROV Liropus 2000, durante la campaña del proyecto CriMa, llevada a cabo en el B/O Sarmiento de Gamboa (septiembre de 2020).

3. Indicadores de vulnerabilidad y conservación de los hábitats

Desde hace décadas, se han utilizado indicadores que facilitan el estudio de los hábitats marinos (Margalef 1951; Dahlberg 1970). Así, indices como los de diversidad (Takahashi y Bienfang 1983; Thomas 1993), nos ofrecen una visión de la calidad y estado de conservación de los hábitats, mientras que los índices de condición de especies como la talla-peso o el índice gonadosomático nos indican el estado de los individuos y las poblaciones, lo cual también tiene una estrecha relación con el propio estado de conservación del hábitat (Lloret et al., 2014; Farré et al., 2016; Pondella et al., 2019).

En ecología, el término vulnerabilidad se define como la susceptibilidad de un individuo, especie, población, comunidad o hábitat a verse afectado por factores externos, ya sean de origen natural o antropogénico (Halpern et al., 2007). En las últimas dos décadas, se ha comenzado a estudiar la vulnerabilidad de las comunidades marinas para conocer la resiliencia de un hábitat a estresores externos, asi como su estado de conservación (Bremner et al., 2003; Bremner 2008; de Juan et al., 2020). En este sentido, avanzar en la investigación acerca de indicadores que puedan utilizarse para conocer la vulnerabilidad al arrastre y el estado de conservación de hábitats impactados, es un paso fundamental para mejorar su gestión. Por este motivo, esta tesis aborda el estudio de la vulnerabilidad a la pesca de arrastre de hábitats bentónicos marinos especialmente productivos y de su estado de conservación mediante el uso de los siguientes indicadores:

a) Supervivencia de invertebrados al descarte de la pesca de arrastre

El descarte está compuesto por capturas no deseadas, que son fundamentalmente individuos de especies comerciales por debajo de la talla legal y especies de nulo o poco valor comercial (Damalas et al., 2015; Blanco et al., 2018). El abanico de taxones que componen el descarte es muy grande y va desde peces óseos y cartilaginosos, hasta invertebrados marinos (Bellido et al., 2011: García-de-Vinuesa 2012; Vilela y Bellido 2015; Tsagarakis et al., 2014). Para la gestión del descarte, hay que tener en cuenta que su composición varía entre hábitats y que no todas las especies mueren tras ser descartadas, ya que hay especies que sobreviven gracias a rasgos biológicos concretos, como la capacidad de regeneración, la resistencia a la emersión, la dureza del caparazón o la elasticidad (WKMEDS 2014; ICES 2020). Por lo tanto, evaluar la capacidad que los animales tienen a sobrevivir al descarte de la pesca de arrastre puede ser un instrumento útil para su gestión y la gestión de los hábitats donde se realiza, ya que nos indica la resistencia y resiliencia que presentan las especies al impacto del descarte, que son cualidades fundamentales dentro del estudio de la vulnerabilidad de las comunidades (de Juan et al., 2020).

Los invertebrados descartados por la pesca de arrastre son necesarios para el correcto funcionamiento de los ecosistemas bentónicos, ya que cumplen con tareas esenciales, como fijar los nutrientes provenientes del ambiente pelágico, formar la base alimenticia para el resto de las especies que allí habitan o funcionar como constructores del propio medio físico (Lohrer et al., 2004; Muntadas et al., 2016). En este sentido, conocer la respuesta de los invertebrados descartados por la pesca de arrastre, es fundamental para conocer la vulnerabilidad del propio hábitat. Sin embargo, hasta ahora se ha estudiado la supervivencia de muy pocas especies de invertebrados no comerciales (Giomi et al., 2008; García-de-Vinuesa 2012; Tsagarakis et al., 2018), ya que la mayoría de estudios atañen a especies comerciales y no se ha tenido en cuenta el papel del hábitat (Campos et al., 2015; Morfin et al., 2017;

Mérillet et al., 2018). Por este motivo, para avanzar en el estudio de la supervivencia de invertebrados al descarte de la pesca de arrastre y de la vulnerabilidad de los hábitats ante dicha pesca, evaluamos la resistencia y resiliencia que los hábitats de crinoideos y los fondos de fango presentan frente al descarte de la pesca de arrastre, identificando en el capítulo 1 qué organismos y donde se ven afectados por esta práctica y evaluando en el capítulo 2, su supervivencia al descarte.

b) Vulnerabilidad de comunidades de infauna al arrastre

Por sus características, la pesca de arrastre afecta directamente a la fauna bentónica, y aunque algunos de estos animales debido a su forma o tamaño no son capturados por la red de arrastre, reciben igualmente su impacto, ya sea de manera directa, al ser arrollados por el arte, o indirecta, al verse afectados por las modificaciones ambientales producidas por el arte, como cambios en la turbidez del agua o la fragmentación del hábitat (Sánchez et al., 2000; Muntadas et al., 2014; Lotze et al., 2019). Debido a este impacto, los organismos con características biológicas vulnerables al arrastre como los de gran tamaño, longevos o filtradores tienden a desaparecer dando paso a organismos más pequeños, de corta vida y oportunistas como los pequeños carroñeros que aprovechan los restos de materia orgánica en forma de cadáveres que el arrastre deja a su paso (Demestre et al., 2000; Kayser 2000; de Juan et al., 2007). En este aspecto, una de las comunidades bentónicas más afectadas por la pesca de arrastre es la comunidad de infauna (Koch et al., 2009; Muntadas et al., 2016). Esta comunidad, varía de manera natural entre hábitats y puede ser transformada por la pesca de arrastre, disminuyendo su diversidad y abundancia. Por este motivo, la pesca de arrastre puede afectar a la funcionalidad del hábitat, disminuyendo o modificando los recursos alimenticios de especies comerciales, afectando a su condición y por ende a sus stocks, alterando entonces, los bienes y servicios ofrecidos por los hábitats (Lohrer et al., 2004; de Juan y Hewitt 2014; Muntadas et al., 2015).

Se ha demostrado que el estudio de los rasgos biológicos de los animales que conforman las comunidades marinas, puede ser muy útil para la construcción de indicadores como el análisis de rasgos biológicos (Biological Trait Approach, BTA, en inglés). El BTA, utiliza conjuntos de rasgos biológicos para conocer la respuesta de comunidades marinas expuestas a estresores naturales o antropogénicos (Usseglio-Polatera et al., 2000; Bremner et al., 2003; de Juan et al., 2011 Muntadas et al., 2016). Hasta ahora, el BTA se ha utilizado para evaluar cambios en la funcionalidad de un hábitat específico o la vulnerabilidad de ciertas comunidades o especies al arrastre (Bremner 2008; Mouillot et al., 2013; Muntadas et al., 2016; de Juan et al., 2020). Sin embargo, esta herramienta no se ha utilizado para estudiar la vulnerabilidad de comunidades de hábitats de maërl, ni para evaluar cómo las propias características de los hábitats los convierten en más o menos vulnerables a la pesca de arrastre. Por este motivo, en el capítulo 3 de esta tesis se utilizó un BTA para evaluar y comparar la vulnerabilidad a la pesca de arrastre de comunidades de infauna procedentes de hábitats de maërl y de fondos fangosos.

c) Ácidos grasos de animales provenientes de hábitats especialmente productivos, explotados por la pesca de arrastre

Los ácidos grasos son componentes fundamentales de todos los animales y están ligados íntimamente a funciones vitales, como el crecimiento o la reproducción (Dalsgaard et al., 2003; Lloret et al., 2014). En los últimos años se ha investigado extensamente en el campo de los ácidos grasos de origen marino, debido fundamentalmente a que se ha demostrado que algunos de ellos, como los omega 3, no pueden ser sintetizados a partir de otros ácidos grasos, por lo que son integrados por los animales exclusivamente a través de la dieta, son esenciales para el desarrollo de los juveniles de peces y para el potencial reproductor de los adultos (Lloret et al., 2014). Además se ha demostrado que ciertos ácidos grasos omega 3, como el acido docosahexaenoico (DHA), pueden ser especialmente beneficiosos para la salud humana, ya que previenen cardiopatías y enfermedades mentales (Rontoyanni et al., 2012; Fard et al., 2019; Chang et al., 2020). Estos ácidos grasos, se encuentran en grandes cantidades en algunas especies pelágicas como la sardina (*Sardina pilchardus*) y la anchoa (*Engraulis encrasicolus*) ya que su producción mas importante al realiza en el fitoplancton marino (Teodosio et al., 2017; Taipale et al., 2020). Pero sus cantidades tampoco son desdeñables en especies demersales como los salmonetes (*Mullus spp.*) y la merluza (*Merluccius merluccius*), gracias entre otros factores, al flujo de nutrientes desde el ambiente pelágico al bentónico, por lo que las especies demersales también son una buena fuente de omega 3 para el hombre (Atehortúa et al., 2017).

Si la pesca de arrastre reduce la abundancia de algunas especies o la diversidad en determinadas comunidades, como en las comunidades de infauna, muchas especies de peces pueden ver alterada su dieta y por ende su fuente de ácidos grasos. Por lo tanto, los ácidos grasos resultan muy útiles para evaluar la condición y salud de los peces (Sargent et al., 1995 a,b; Dalsgaard et al., 2003; Lloret et al., 2014), a la vez que son buenos indicadores para estudiar la calidad y el estado de conservación de los hábitats, sobre todo los expuestos a estresores naturales o antropogénicos. Sin embargo, los ácidos grasos rara vez se han usado en este sentido (Levi et al., 2005; Arechavala-Lopez et al., 2019) y nunca se han utilizado como indicadores para evaluar el impacto de la pesca de arrastre sobre los hábitats. Por este motivo, en el capítulo 4 de esta tesis, se utilizaron los ácidos grasos de salmonetes y de sus presas de la infauna, como indicadores para determinar la calidad y el estado de conservación de hábitats de maërl y fondos de fango explotados por la pesca de arrastre.

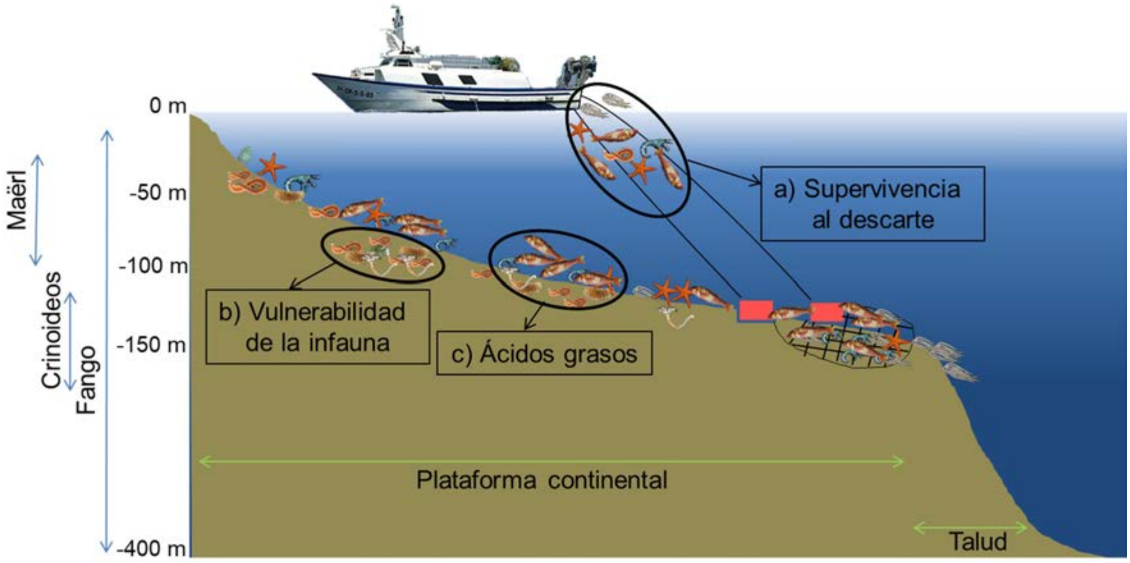


Figura 7.- Ordenación batimétrica de los hábitats estudiados en esta tesis y procedencia de los indicadores.

4. La gestión actual de la pesca de arrastre: aún lejos de un equilibrio entre explotación y conservación.

a) Estado actual

Hasta ahora, las medidas de gestión aplicadas no han contribuido a la disminución de los niveles de sobreexplotación de muchas especies comerciales afectadas por la pesca de arrastre en el Mediterráneo (Khoukh y Maynou 2018; Ordines et al., 2019). Muchas de estas especies como la merluza, el salmonete o el pulpo son también objetivo para otros tipos de pesca como las artesanales, por lo que la gestión de la pesca de arrastre puede afectar a la diversidad y cantidad de sus capturas (Martín et al., 2019). Actualmente, la problemática social generada por la sobreexplotación de los estocs es grande, ya que a fin de intentar recuperar el equilibrio en las poblaciones explotadas, varios países están ajustando la capacidad de sus flotas a los recursos disponibles, por lo que el número de embarcaciones de pesca en el Mediterráneo disminuyó en unas 6 000 embarcaciones (el 6 %) desde 2016 hasta 2018, lo que ha supuesto una disminución importante de los empleos del sector (FAO 2018).

Aunque en otras pesquerías mediterráneas de tipo artesanal se ha demostrado que la cogestión de la administración junto a pescadores, científicos y Organizaciones No Gubernamentales (ONGs), puede ser exitosa para la recuperación de estocs y la revalorización del producto pesquero en el mercado (Lleonart et al., 2014), este enfoque no se aplica actualmente a la pesca de arrastre. Además, el enfoque regional se ha comenzado a incorporar pocos años atrás por la Unión Europea, que no tenía en cuenta características fundamentales de las pesquerías mediterráneas, como la multiespecificidad, por lo que algunas normativas aplicadas a las pesquerías de países del norte de Europa, son todavía aplicadas también en el Mediterráneo, siendo ineficientes para la gestión de la zona (Casado 2008). Otro problema son las trabas burocráticas y la falta de interés o conocimiento de la administración para aplicar las normativas vigentes y adaptarlas a las nuevas recomendaciones científicas en el Mediterráneo. Por lo que en muchas ocasiones el esfuerzo científico y legislativo no se aprovecha convenientemente (Muntadas et al., 2015).

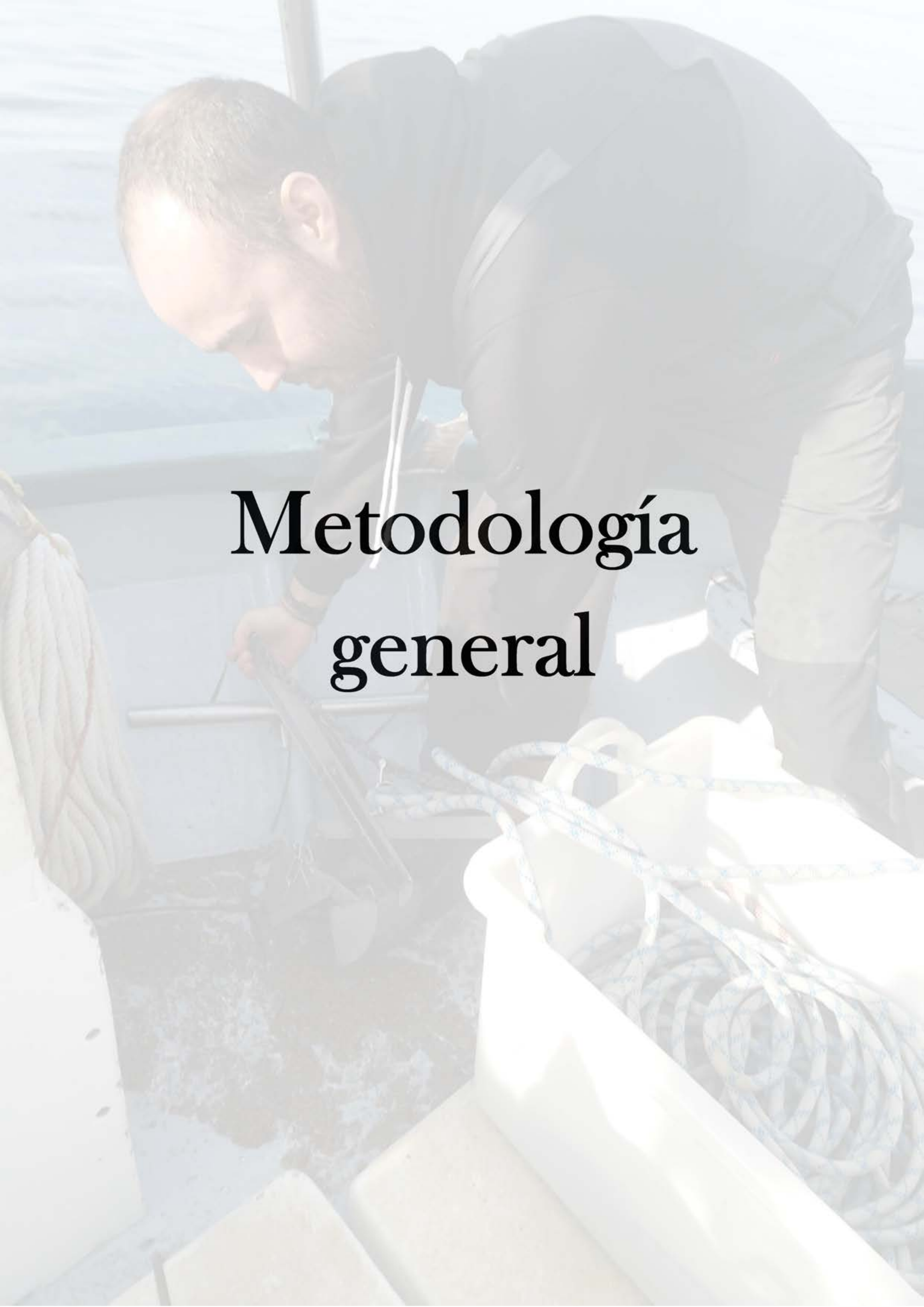
b) Medidas de gestión específicas sobre la pesca de arrastre del Mediterráneo

Actualmente, la gestión de la pesca de arrastre llevada a cabo por la comunidad europea en el mar Mediterráneo se basa principalmente en el control del esfuerzo pesquero. Así, la pesca de arrastre se prohíbe a menos de 50 metros de profundidad y/o a menos de 1.5 millas náuticas de costa, y a más de 1000 metros de profundidad (EU Reg. 1967/2006). Existen en el Mediterráneo, zonas cerradas a la pesca en forma de Áreas Marinas Protegidas (AMPs) y vedas estacionales, que comprenden desde uno a cuatro meses (Martin et al., 2014). La potencia de los motores también está regulada (Cacaud 2005) con un máximo de 500 CV, que al menos en el caso de la costa catalana son teóricos, ya que la mayoría de los patrones admiten tener una potencia declarada y otra real (observación personal). Además, se obliga a las embarcaciones de más de 15 metros de eslora, a llevar un sistema de monitoreo por satélite (Vessel Monitoring System, VMS) cuyos datos son enviados periódicamente a las autoridades competentes. Sin embargo, estas medidas de control del esfuerzo pesquero se han mostrado hasta ahora poco efectivas para solventar problemas ecológicos generados por la pesca de arrastre (Muntadas et al., 2014; Damalas et al., 2015; Bellido et al., 2017). Las áreas marinas protegidas suelen establecerse en zonas muy costeras con menos de 50 metros de profundidad, que por normativa no deberían estar afectadas por la pesca de arrastre por lo que en general no tienen en cuenta los potenciales hábitats esenciales para peces, situados a mayor profundidad como podrían ser hábitats de crinoideo, maërl y determinados fondos de fango (Gray 2002; Demestre et al., 2017; Leonard et al., 2020). Por otro lado, las vedas estacionales son demasiado breves para la recuperación de la fauna bentónica (Dinmore et al., 2003; Demestre et al., 2008). Además, el control del posicionamiento a través del sistema de monitoreo por satélite pierde utilidad puesto que no se conoce la localización exactas de hábitats vulnerables, como los hábitats de maërl, donde el arrastre está prohibido (EU Council Regulation 1967/2006; Basso et al., 2017).

Para el arrastre llevado a cabo en el Mediterráneo, la comunidad europea también regula aspectos técnicos, como las medidas mínimas para las redes de arrastre que deben tener un máximo de luz de malla en el copo de 40 mm cuadrada o 50 mm diamante, o la obligación de desembarque (en inglés Landing Obligation, LO), aplicable a determinadas especies comerciales capturadas que tienen una talla mínima de referencia (en inglés, Minimum Conservation Reference Size, MCRS). Dentro de esta nueva ley se establecen excepciones para especies que muestren alta supervivencia al descarte (EU Regulation 1380/2013). Sin embargo, hay pocos estudios acerca de la supervivencia de especies descartadas en el Mediterráneo (Giomi et al., 2008; García-de-Vinuesa 2012; Tsagarakis et al., 2018), comparado con otras zonas europeas, como el Atlántico portugués, francés, o el mar del Norte (Castro et al., 2003; Albalat et al., 2010; Campos et al., 2015; Mérillet et al., 2018). Otra problemática de la actual normativa que regula la pesca de arrastre, se refiere a la talla de primera madurez de especies como el salmonete, la merluza o la cigala, que son tallas sustancialmente superiores a sus tallas mínimas de referencia o tallas legales de captura (Follesa et al., 2019; Carbonara et al., 2019; Angelini et al., 2020).

Todas estas medidas, están enfocadas a la biología de especies comerciales y no tienen en cuenta los hábitats, ya que sus comunidades están conformadas por multitud de especies no comerciales que se ven de igual manera, perjudicadas por el impacto de la pesca de arrastre (Dinmore et al., 2003; Demestre et al., 2008; Muntadas et al., 2016). En este contexto, en las últimas décadas el enfoque de la gestión a partir de la protección de los EFH, ha ido ganando terreno (Link 2002; Frid et al., 2005) y la Unión Europea a través de la estrategia marina establecida en 2008 (EC 2008/56) alienta a los estados miembros a aplicar una gestión pesquera basada en los ecosistemas (en inglés, Ecosystem-Based Fisheries Management, EBFM) para lograr un equilibrio entre la explotación y la conservación de los mismos. Sin embargo, aunque muchos países están trabajando en implementar este enfoque para la gestión de sus pesquerías, aún tiene un bajo grado de desarrollo tanto a nivel global, como en el Mediterráneo (Pitcher et al., 2009; Sartor et al., 2014).

Metodología general



Esta tesis doctoral, ha sido desarrollada en el marco de varios proyectos de investigación: el proyecto MINOUW (H2020-SFS-2014-2) financiado por la Unión Europea, que tuvo como objetivo la disminución de la captura no deseada; el Proyecto CriMa, financiado por el Ministerio de Ciencia, Innovación y Universidades del Gobierno de España y los fondos FEDER de la UE (RTI2018-095770-B-100-MCIU/AEI/FEDER,EU), que tiene como objetivo el estudio de hábitats de maërl y agregaciones de crinoideos para identificar su Buen Estado Ambiental (en inglés, Good Enviromental status, GES) y conservar sus bienes y servicios potenciando el consolidar su marco de integridad ecológica en relación a los efectos de la pesca para para mejorar su gestión actual; y los proyectos GALP-Costa Brava Omega 3 y Cap de Creus financiados por el Fondo Europeo Marítimo y Pesquero, la Generalitat de Cataluña, y la fundación la Caixa respectivamente, que tuvieron como objetivo común el estudio de los ácidos grasos en fondos de maërl y fangosos para la mejora de su gestión.

a) Área de estudio

El área de estudio de esta tesis estuvo situada íntegramente en el Mediterráneo noroccidental, donde se escogió un área perturbada por la pesca de arrastre (Blanes) y un área no perturbada por la pesca de arrastre (Roses). Además, excepcionalmente para la consecución de los objetivos del capítulo segundo de esta tesis, se tuvo en cuenta otra área impactada por la pesca de arrastre situada en el norte del mar Tirreno (Figura 1).

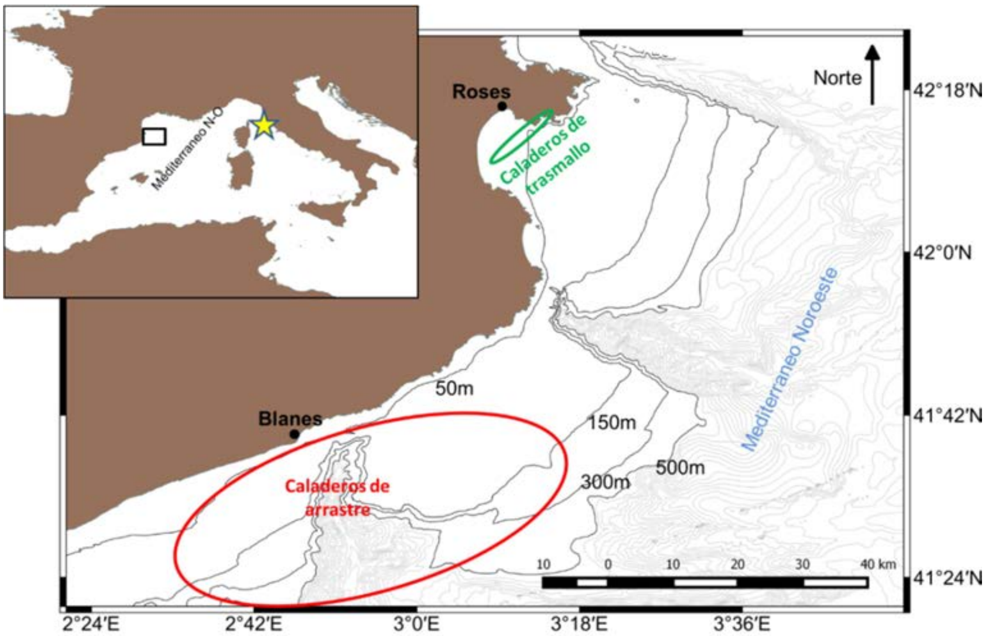


Figura 8.- Área de estudio situada al noroeste del mar Mediterráneo. Al norte, el área de Roses cuyos caladeros están protegidos de la pesca de arrastre y al sur, el área de Blanes cuyos caladeros están afectados por la pesca de arrastre. Además se indica con una estrella amarilla el área de Liguria al norte del mar Tirreno, tenido en cuenta en el segundo capítulo de esta tesis.

Como en el mar Mediterráneo la pesca de arrastre está prohibida a menos de 50 metros y a más de 1000 metros de profundidad, el rango de profundidad de los caladeros frecuentados por la pesca de arrastre seleccionados varió desde los 54 hasta los 530 metros, mientras que los caladeros donde se prohíbe la pesca de arrastre (solo se lleva a cabo pesca de trasmallo), se situaron entre los 21 y los 40 metros de profundidad (Tabla 1). En Blanes, las barcas de arrastre tienen permitida su actividad durante 12 horas al día de lunes a viernes, existe una veda temporal de un mes que suele llevarse a cabo en el mes de febrero y una veda de seis meses en uno de sus caladeros menos profundos. El área de pesca de arrastre de Blanes es amplia, y muestra una gran heterogeneidad entre sus caladeros ya que en el capítulo 1 de esta tesis localizamos hábitats de fango, maërl y agregaciones de crinoideos distribuidos entre seis caladero, donde las especies objetivos son merluza, rape, salmonete, pulpo, "espardenya" (holoturia), pagel, cigala y gamba blanca. Debido a las restricciones horarias y territoriales de la pesca de arrastre en Cataluña, la única flota que explota estos caladeros es la ubicada en el puerto más cercano. En este caso las 28 barcas de la flota arrastrera del puerto de Blanes. Excepcionalmente, en el capítulo 2 de esta tesis para el estudio de supervivencia del descarte de la pesca de arrastre se tuvo también en cuenta además de dos caladeros de fango y uno de agregación de crinoideos en la zona de Blanes, un caladero situado sobre un hábitat de fango que se encuentra en la zona norte del mar Tirreno, a una profundidad de entre 85 y 470 metros. Por último, en los capítulos 3 y 4 comparamos 2 habitats situados en calderos de Blanes, uno de maërl situado entre 55 y 107 m de profundidad y uno fangoso situado entre 71 y 113 metros de profundidad con dos hábitats situados en dos caladeros adyacentes al puerto de Roses, donde solo la pesca artesanal está permitida. En estos últimos dos caladeros encontramos un hábitat de maërl situado dentro de la reserva marina del Cap de Creus, concretamente en la cala Montjoi entre los 21 y 35 metros de profundidad y un fondo fangoso situado en la bahía de Roses, entre 25 y 40 metros de profundidad.

Tabla 1. Características de los caladeros estudiados. Se muestra el nombre de cada caladero, el tipo de pesca permitido (Pesca), la profundidad mínima en metros (P min (m)), la profundidad máxima en metros (P máx (m)) y el tipo de hábitat.

Caladero	Pesca	Localización	P min (m)	P máx (m)	Hábitat
Capets	Arrastre	Area de Blanes	71	113	Fango
Fluviana			93	144	Crinoideos
Las 40			83	102	Fango
Garotes			55	107	Maërl
Malica			196	494	Fango
Planassa			86	530	Fango-crinoideos
Cala Motjoi	Trasmallo	Area de Rosas	21	35	Maërl
Bahia de Rosas			25	40	Fango
Argentario	Arrastre	Liguria	85	470	Fango

b) Muestreo

Los diferentes muestreos se llevaron a cabo entre marzo de 2016 y octubre de 2018. A partir de estos muestreos se identificaron 48 especies comerciales, 152 especies procedentes del descarte y 44 familias de infauna (Anexo I). Entre marzo de 2016 y febrero de 2017, se llevó a cabo la identificación de hábitats, mediante la caracterización de 23 muestras de descarte de la pesca de arrastre del área de Blanes y se estudió la dinámica de la flota a partir del análisis de datos del sistema de monitoreo de embarcaciones (VMS, Vessel Monitoring System) junto con los datos de Toneladas de Registro Bruto (TRB) de la flota de Blanes a través de un sistema de información geográfica (en inglés, Geographic Informatic System, GIS) (capítulo 1). Tras los primeros meses de muestreo, que sirvieron para seleccionar especies representativas del descarte de varios hábitats, se comenzó a estudiar la supervivencia de invertebrados al descarte, que concluiría al igual que la identificación de los hábitats, en febrero de 2017 (capítulo 2). Para muestrear se utilizó el propio arte de arrastre de cuatro embarcaciones de eslora comprendida entre 14 y 26.5 metros, con abertura de la boca de entre 14 y 30 metros y un copo con una luz de malla de 50 mm romboidal o 40 mm cuadrado, arrastrado a una velocidad de entre 2.4 y 3.2 nudos. Los datos VMS, correspondieron a los años 2012, 2013 y 2014 y fueron provistos por el Ministerio de Agricultura, Pesca y Medio Ambiente (MAGRAMA). El resto de muestreos se llevaron a cabo siempre durante los meses de octubre, en 2016, 2017 y 2018, para evitar la componente estacional. De esta manera en octubre de 2016 durante la campaña oceanográfica Deep Visión II en Blanes, y en octubre de 2017 a bordo de un trasmallero comercial en Roses, se llevaron a cabo muestreos de infauna usando una draga Van Veen con una superficie de 0.1 m^2 sobre un caladero de maërl y otro de fango en ambas zonas (capítulo 3). Para estos muestreos de infauna se tomaron 3 muestras en zonas aleatorias de cada caladero, cada una de ellas compuesta por 5 dragas para alcanzar el tamaño mínimo de la muestra, como se explica en de Juan et al. (2007). En Octubre de 2017, para el estudio de ácidos grasos (capítulo 4) se muestrearon salmonetes desde un trasmallero comercial en el área de Roses procedentes del mismo hábitat fangoso y de maërl donde se muestreó la infauna. Por último en octubre de 2018 se muestrearon salmonetes de una barca de arrastre de Blanes procedentes de los mismos hábitats de maërl y fango en los que se llevó a cabo el muestreo de infauna en 2016.

Tabla 2. Características del muestreo. Se muestran las fechas, el área, el tipo de muestras y el número de muestras (N)

Fecha	Area	Tipo de Muestra	N
mar-16/feb-17	Blanes y Liguria	Descarte	23
oct-16	Blanes	Infauna	30
oct-17	Roses	Infauna y salmonete	30 y 68
oct-18	Blanes	Salmonete	46

c) Análisis de muestras

Las muestras utilizadas para la caracterización del descarte de la pesca de arrastre, fueron en su mayoría submuestras del total del descarte (entre 7 y 10 kg), y fueron trasladadas hasta el Instituto de Ciencias del Mar (ICM) en Barcelona, para su estudio (capítulo 1). Los animales del descarte seleccionados para el estudio de la supervivencia, fueron algunos estudiados a bordo y otros trasladados en condiciones adecuadas hasta la zona de acuarios experimentales del ICM-CSIC para su mantenimiento, siguiendo las indicaciones del Workshop on Methods for Estimating Discard Survival (WKMEDS 2014) (capítulo 2). Se tomaron medidas de los salmonetes muestreados y se conservó todo el músculo posible congelado, en un primer momento en nitrógeno líquido y posteriormente a -80 ºC en el ICM hasta el análisis de ácidos grasos. Este mismo proceso de conservación se siguió con parte de los organismos de la infauna que se utilizarían después para el análisis de sus ácidos grasos, que fue llevado a cabo en un laboratorio externo cuya metodología se detalla en el capítulo 4 de esta tesis. La parte restante de infauna fue fijada en formol hasta su clasificación a mínimo taxón posible en el laboratorio (capítulo 3).

Figura 9.- Cangrejo ermitaño (*Dardanus arrosor)* utilizado en el estudio de supervivencia al descarte de invertebrados de la pesca de arrastre que se ha llevado a cabo en la Zona de Acuarios Experimentales (ZAE) del ICM-CSIC

Objetivos

El objetivo principal de esta tesis doctoral fue **evaluar la vulnerabilidad a la pesca de arrastre y el estado de conservación de ecosistemas bentónicos marinos especialmente productivos del Mediterráneo mediante el uso de indicadores novedosos que puedan ser aplicados a la gestión de dichos hábitats.**

Este objetivo principal está dividido en 4 objetivos específicos, que son necesarios en su conjunto para la consecución del objetivo principal (figura 10). Los 4 objetivos específicos de la tesis corresponden cada uno a un capitulo concreto. Específicamente, el objetivo 1 proporcionó la base sobre la que se desarrollan los objetivos 2, 3 y 4. Por último, a partir de los resultados obtenidos en la consecución de todos los objetivos, se han hecho un conjunto de recomendaciones a través de la discusión global para avanzar hacia una gestión de los hábitats equilibrada entre explotación y conservación.

Figura 10.- Relación existente entre capítulos y objetivos de la tesis

Objetivos específicos:

1. **Identificar ecosistemas bentónicos marinos mediterráneos especialmente productivos mediante la caracterización del descarte de la pesca de arrastre y cuantificar el impacto pesquero al que se ven sometidos**. Para la consecución de éste objetivo, en el **capítulo 1** se caracterizó el descarte de 4 barcas de arrastre que faenan en 6 caladeros adyacentes al puerto de Blanes y se relacionó con la dinámica de la flota arrastrera a partir de datos VMS.

2. **Evaluar la supervivencia al descarte de especies representativas de ecosistemas especialmente productivos.** Este objetivo se desarrolla en la **sección "a"** del **capítulo 2** a partir de la valoración de la vitalidad y supervivencia de especies de invertebrados descartables a bordo de embarcaciones de arrastre y en acuarios. A partir de los resultados de la sección "a", en la **sección "b"** del **capítulo 2** se eligió una de las especies características de fondos de fango, la cigala (*Nephrops norvegicus),* con posibilidades de alta supervivencia al descarte, ya que era una buena candidata a una excepción de la obligación de desembarque. Con estas premisas se llevó a cabo un estudio estacional de su supervivencia al descarte de la pesca de arrastre.

3. **Evaluar y comparar la vulnerabilidad a la pesca de arrastre de comunidades de infauna procedentes de hábitats especialmente productivos.** En el **capítulo 3**, se evaluó y comparó por medio de un análisis de rasgos biológicos, la vulnerabilidad al arrastre de comunidades de infauna procedentes de hábitats de maërl y de fango.

4. **Evaluar la calidad y el estado de conservación de hábitats especialmente productivos explotados por la pesca de arrastre a partir del estudio de los ácidos grasos de salmonetes y de sus presas.** En el **capítulo 4** se probó la validez del uso de ácidos grasos de salmonetes e infauna provenientes de hábitats de maërl y de fango como indicadores de calidad del hábitat y de su perturbación por parte del arrastre, discutiendo a la vez, la validez de su uso como marcador trófico en ecosistemas bentónicos.

Informe de los directores

La Dra. Montserrat Demestre Alted y el Dr. Josep Lloret Romañach, directora y codirector respectivamente de la tesis doctoral depositada por el Sr. Alfredo García de Vinuesa Gutiérrez en la Universidad de Barcelona, certifican que todos los estudios incluidos como capítulos en su tesis han sido sometidos a revistas científicas internacionales sujetos a un proceso de "peer review" por parte de revisores ("referees") externos e independientes. Tres de estos trabajos ya han sido publicados mientras que los otros dos, se han sometido y están en proceso de evaluación.

Los detalles de cada publicación se indican a continuación:

Capítulo 1:

Linking together trawl fleet dynamics and the spatial distribution of exploited species can help to avoid unwanted catches: the case of the NW Mediterranean fishing grounds.

Alfredo Garcia-de-Vinuesa, Iván Sola, Federico Quattrocchi, Francesc Maynou, Montserrat Demestre. 2018. Linking together trawl fleet dynamics and the spatial distribution of exploited species can help to avoid unwanted catches: the case of the NW Mediterranean fishing grounds. Scientia Marina 2018, 82S1:165-174, https://doi.org/10.3989/scimar.04755.17A

Estado: publicado

Índice de impacto: **1.183; Q2**

Capítulo 2:

Ecological importance of survival of unwanted invertebrates discarded in different NW Mediterranean trawl fisheries.

Demestre M. , Sartor P., **Garcia-de-Vinuesa A**., Sbrana M.., Maynou F., Massaro A. 2018 Ecological importance of survival of unwanted invertebrates discarded in different NW Mediterranean trawl fisheries. Scientia Marina. 2018, 82S1:189-198, https://doi.org/10.3989/scimar.04784.28A

Estado: publicado

Índice de impacto: 1.183; Q2

Seasonal variation in the survival of discarded *Nephrops norvegicus* in a NW Mediterranean bottom-trawl fishery.

Alfredo Garcia-de-Vinuesa, Mike Breen, Hugues P. Benoît , Francesc Maynou and Montserrat Demestre. 2020. Seasonal variation in the survival of discarded *Nephrops norvegicus* in a NW Mediterranean bottom-trawl fishery. Fisheries Research 2020, 230:1-8, https://doi.org/10.1016/j.fishres.2020.105671

Estado: publicado

Índice de impacto: **2.147; Q1**

Capítulo 3:

Importance of habitat characteristics in determining the vulnerability of infaunal organisms to trawling.

Alfredo Garcia-de-Vinuesa, Josep Lloret and Montserrat Demestre. 2020. Importance of habitat characteristics in determining the vulnerability of infaunal organisms to trawling. Aquatic conservation: Marine and Freshwater Ecosystems.

Estado: en revision (sometido)

Índice de impacto: **2.935; Q1**

Capítulo 4:

Fatty acids as health indicators of exploited benthic habitats in the Mediterranean: the case of maerl beds and muddy bottoms.

Alfredo Garcia-de-Vinuesa, Montserrat Demestre and Josep Lloret. 2020. Fatty acids as health indicators of exploited benthic habitats in the Mediterranean: the case of maerl beds and muddy bottoms. Estuarine and Coastal Shelf Science.

Estado: en revisión (sometido)

Índice de impacto: **2.611; Q1**

El candidato Alfredo García de Vinuesa Gutiérrez se ha involucrado intensamente en todos estos capítulos / artículos. Concretamente, en los 4 artículos que figura como primer autor, ha liderado el artículo en todos los sentidos, desde el diseño del estudio, el muestreo, el análisis e interpretación de los datos y el escrito del artículo en sí. En el artículo del capítulo 2 en que figura como coautor, el candidato ha diseñado el estudio, realizado íntegramente el muestreo, ha contribuido de manera esencial en los análisis e interpretación de los datos y ha liderado la escritura de los resultados y la discusión del artículo.

Con todos estos trabajos el candidato ha logrado unos excelentes conocimientos sobre la materia. El candidato ha realizado los trabajos de manera diligente, participando activamente en los proyectos de investigación en los que se han desarrollado sus tareas. La calidad de las revistas donde ha publicado los trabajos demuestra el carácter innovador y la calidad de las investigaciones que configuran su tesis doctoral.

Barcelona, 16 de octubre de 2020

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Universitat de Girona

Resultados

Capítulo 1

Linking trawl fleet dynamics and the spatial distribution of exploited species can help to avoid unwanted catches: the case of the NW Mediterranean fishing grounds

Linking trawl fleet dynamics and the spatial distribution of exploited species can help to avoid unwanted catches: the case of the NW Mediterranean fishing grounds

Alfredo García-de-Vinuesa, Iván Sola, Federico Quattrocchi, Francesc Maynou and Montserrat Demestre

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Publicado: Scientia Marina 82S1 Octubre 2018, 165-174

https://doi.org/10.3989/scimar.04755.17A

Summary: With the full implementation of the landing obligation on 1 January 2019, In European waters it will become mandatory for the trawling fleet to land at port all catches of certain species because, according to Article 15 of the new European Common Fisheries Policy, the species subject to the minimum conservation reference size (MCRS) cannot be discarded. Additionally, since 2005, trawlers over 15 m in length are required to carry an onboard vessel monitoring system (VMS), which generates information on fleet dynamics. The objective of this work was to provide a tool for avoiding unwanted catches by integrating the catch study of trawlers operating in the port of Blanes together with VMS data. To achieve this objective, the catches of 40 hauls were monitored, sampled and analysed together with VMS data for the years 2012-2014 integrated in a geographical information system. The results show that specimens below the MCRS were often captured in crinoid aggregation habitats, bottoms with maerl and muddy bottoms that were identified as nursery habitats of commercial species, e.g. *Merluccius merluccius*, *Pagellus spp*. and *Mullus spp*. VMS data showed considerable fishing pressure on areas with maerl and muddy habitats during the recruitment periods of these and other commercially relevant species. Implementing spatial or seasonal closures in habitats where species regulated by the MCRS are subject to catches could be a useful tool for preventing unwanted catches.

Keywords: unwanted catches; northwestern Mediterranean; trawl fishery; discard; VMS; MCRS.

Vincular la dinámica de la flota de arrastre y la distribución espacial de las especies explotadas puede ayudar a evitar capturas no deseadas: el caso de los caladeros del Mediterráneo noroccidental

Resumen: Con la plena aplicación de la Obligación de desembarque a partir del 1 de enero de 2019, pasará a ser obligatorio para la flota de arrastre desembarcar en puerto todas las capturas de ciertas especies, que según el Artículo 15 de la nueva política pesquera común no pueden ser descartadas, ya que están sujetas a MCRS. Por otro lado, desde 2005, se requiere a los arrastreros de más de 15 m de longitud, llevar a bordo un VMS, que proporciona información acerca de la dinámica de la flota. El objetivo de este trabajo fue proporcionar una herramienta para evitar capturas no deseadas integrando el estudio de la captura de arrastreros que operan en el puerto de Blanes junto con datos VMS de la flota de arrastre. Para lograr dicho objetivo, las capturas de 40 lances fueron monitoreadas, muestreadas y analizadas junto con los datos VMS de los años 2012-2014 integrados en un Sistema de Información Geográfica. Los resultados muestran que se capturaron de forma notable especímenes por debajo de la MCRS en hábitats de agregación de crinoideos, fondos con presencia de maerl y fondos fangosos que fueron identificaron como hábitats de cría para especies como *Merluccius merluccius*, *Pagellus spp*. y *Mullus spp*. Los datos VMS mostraron una notable presión pesquera en hábitats fangosos y fondos con presencia de maerl durante los períodos de reclutamiento de estas y otras especies comerciales relevantes. El uso de cierres espaciales o temporales en hábitats sujetos a descarte de especies reguladas por MCRS podría ser una herramienta útil para evitar capturas no deseadas.

Palabras clave: capturas no deseadas; Mediterráneo noroccidental; pesca de arrastre; descarte; VMS; MCRS

1. Introduction

The European Commission defines discarding as the practice of returning unwanted catches to the sea, dead or alive, because they are too small, the fisherman has no quota, or certain catch composition rules apply. This practice has been recognized globally among the most important issues for fisheries management because it is considered a source of uncertainty in the assessment of commercial stocks and negatively affects biodiversity and community structure (Bellido et al., 2011; Tsagarakis et al., 2014).

The sustainable exploitation of marine ecosystems and their natural resources is one of the fundamental goals of the strategy of the European Union (EU) in the framework of research and development (Horizon 2020). For this purpose, the new Common Fishery Policy aims to reduce or avoid unwanted catches as much as possible and, if necessary, to maximize their utilization (non-human consumption) without creating a market for species with an MCRS (EU Reg. 1380/2013). It therefore aims to gradually eliminate discards from community waters.

The reasons for discarding are many and varied and can be driven by economic, sociological, environmental or biological factors (Damalas et al., 2015). In the Mediterranean, total discards have been estimated at 18.6% of the total catch (Tsagarakis et al., 2014). However, bottom trawling is one of the least selective fishing methods (Sommer 2005) and the one with the largest discard of biomass production, accounting for an average of 32.9% of the total catch (Tsagarakis et al., 2014). This discard is less pronounced (<20%) in deep water trawl fisheries, where exploitation targets a single resource, *Aristeus antennatus*, which is exploited between 405 and 773 m (Sanchez et al., 2004). For this reason, in our work, red shrimp fishing grounds were not considered due to the low discard amount in this depth zone in comparison with other shallower fishing grounds and because this discard is mainly composed of non-commercial species (Gorelli et al., 2016) that do not fall under the landing obligation (Article 15 of EU Reg. 1380/2013). On the other hand, previous studies in the Catalan Sea at upper slope depths (between 200 and 400 m) showed that *Nephrops norvegicus* trawl fishery discard rates can be considerable, and species with high commercial value, such as *N. norvegicus* and *Parapenaeus longirostris*, are discarded (García-de-Vinuesa 2012). Lastly, trawl fisheries on the continental shelf typically target several species, such as the high-value *Stichopus regalis*, *Mullus spp*., *Loligo vulgaris*, *Merluccius merluccius* and *Lophius spp*. between 50 and 200 m, where the discarded percentage of the catch may be approximately 60% or higher (Carbonell et al., 2003; Sanchez et al., 2004; Durell et al., 2008).

The capture of juveniles is one of the main reasons for discarding in the Mediterranean Sea (Bellido et al., 2017), and some vulnerable and highly productive Mediterranean zones (such as maerl beds or crinoid aggregations located on the continental shelf and slope) function as nursery areas and are negatively affected by this type of discard (Colloca et al., 2004; Barberá et al., 2003; Hall-Spencer et al., 2003). Maerl beds have been studied for decades, and they are particularly susceptible to physical disturbance (De Juan et al., 2013); although they are protected in Annex I of the Habitat Directive (EU Dir. 92/43/EEC), fishing pressure is still exerted on them (Demestre et al. 2017). However, crinoid aggregation ecosystems have been less studied (Colloca et al., 2004; Reale et al., 2005; Porporato et al., 2010), and unfortunately have no specific legal protection. Many of the commercial species habitually discarded by trawling operations in these ecosystems will soon be affected by the new European landing obligation.

In the European waters of the Mediterranean Sea, the management of bottom trawling is carried out mainly through fishing effort controls, which may not be an effective system for discard management (Damalas et al., 2015). Trawl fishing is prohibited at less than 50 m depth, more than 1000 m depth and less than 1.5 nautical miles of the coast (EU Reg. 1967/2006); other restrictions include marine protected areas and temporal closures, which, in the case of the Spanish Mediterranean trawl fleet, are usually applied for one or two months per year. Technical measures include an MCRS for the main target species under Article 15 of EU Reg. 1380/2013, which specifies that animals below their MCRS should be landed at port. In addition, size regulations for nets are in place, specifying that 40 mm square-mesh net or 50 mm diamond-mesh net must be used for the cod-end (EU Reg. 1967/2006). In the Spanish Mediterranean control of the fleet, the number of hours and days at sea is limited, and since 2005, in European waters fishing vessels exceeding 15 m overall length must be equipped with a satellite-based vehicle monitoring system (VMS) (EU Reg. 404/2011) that, at least every two hours, provides data to the fisheries control authorities on the location, course and speed of vessels. This is one of the latest systems for controlling fishing effort adopted by European fleets operating in the Mediterranean Sea, where VMS has been proven to provide reliable information on habitat impacts (Hinz et al., 2013).

VMS together with other technical vessel data can be used to determine fishery fleet effort and its spatial and seasonal dynamics, which help identify the priority areas/seasons for management (Martín et al., 2014; Demestre et al., 2015). This knowledge, along with catch data, can be used to identify especially vulnerable or productive habitats in order to propose seasonal bans or enforce no-take areas to avoid unwanted catches below the MCRS.

Species covered under European legislation in the Mediterranean (Annex III of EU Reg. 1967/2006) include 20 fish, 4 crustaceans and 3 mollusc bivalves that are affected by MCRS. In addition, local level fishery control measures can often be more restrictive. Particularly in Catalonia, when taking into account European, national and local regulations, the number of species affected by size and/or weight regulations includes 34 fish, 5 crustaceans, 6 bivalves, 1 gastropod, 1 cnidarian, 3 echinoderms and 1 cephalopod (Generalitat de Catalunya 2015). Species only affected by local regulations are not subject to landing obligations, but when they are below the legal size or weight, they must be discarded and cannot be kept on board. Different regulations for a large number of species from the same fishery could involve an operational problem for fishing activities.

Considering the importance of the new European discard regulation, this work proposes to link VMS with discard catch data, paying special attention to the species regulated by MCRS, and at the local level for a representative trawling fleet from the port of Blanes, Catalonia (NW Mediterranean), in order to propose management measures that avoid or minimize unwanted catches.

2. Materials and methods

2.1 Study area

The study area is located in the northwest Mediterranean Sea, comprising five fishing grounds located in the vicinity of a submarine canyon that is frequented by the trawl fleet from the port of Blanes (Fig. 1).

Four of the fishing grounds chosen for the study are on the continental shelf, normally in the depth range of 54 to 145 m (Table 1). Uniquely, at Planassa, the depth reaches 530 m, as this fishing ground includes the northeastern edge of the Blanes canyon. The fifth fishing ground is located on the upper slope, between 196 and 494 m depth.

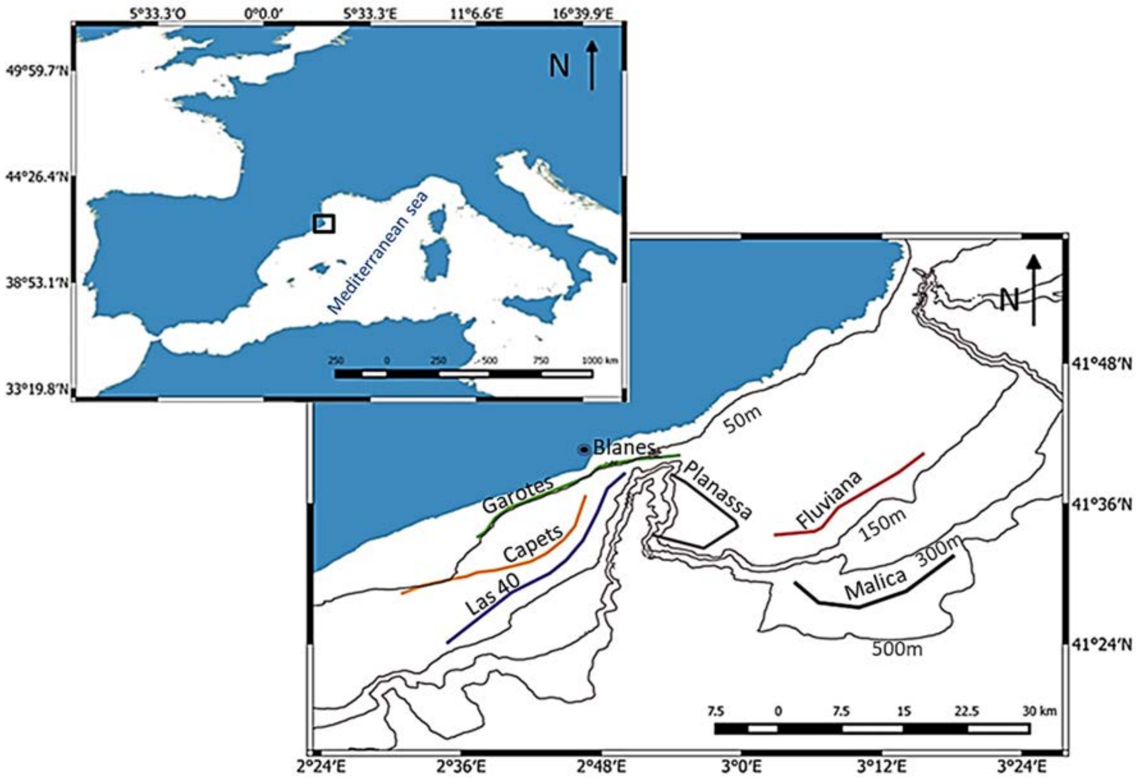

Fig. 1. – Study area indicating the six studied fishing grounds adjacent to Blanes port (northwestern Mediterranean).

2.2 Data source

Between March 2016 and February 2017, sampling was carried out on four commercial trawlers in areas where discard activities were common. Generally, two field trips per month were carried out, one on the continental shelf where three vessels worked, and one on the upper slope where one vessel worked. It was attempted to completely cover the possible spatiotemporal variability at the fishing grounds worked by the Blanes trawl fleet, with the exception of the deepest fishing ground where *Aristeus antennatus* was the target species. Between 1 and 3 hauls were carried out on each fishing trip. In total, 40 hauls were analysed on board, from which biomass and abundance of commercial catch by species were recorded along with the biomass of regulated and unregulated discard.

From 23 hauls, between 7 and 10 kg of the discard fractions were randomly selected and transported to the laboratory, where the organisms were classified to the lowest possible taxonomic level. Abundance and biomass of each species were obtained, and the individuals regulated by MCRS or local regulations were measured.

During the fishing trips, effective trawl time, initial and final position and speed during trawl (2.4-3.2 knots) were recorded. Technical vessel data such as gross tonnage (GT) and overall length were also recorded. Finally, distance between trawl wings was provided by previous measurements carried out by fishermen.

VMS data of the Blanes port trawl fleet for the years 2012, 2013 and 2014 were provided by the Ministerio de Agricultura, Pesca y Medio Ambiente (MAGRAMA) (Spanish Ministry of Agriculture, Fisheries and Environment).

2.3 Data analysis

Biomass (B) and abundance (AB) of discard by species were extrapolated to the total fraction of discards with the formula:

$$\text{Species } AB \text{ } or \text{ } B = \frac{\text{AB or B(Species sampled)} \times \text{AB or B (Total discard)}}{\text{AB or B (Discard sampled)}}$$

After, discard and commercial species abundance and biomass were standardized to hectare respectively using technical vessel, cruise and catch data as follows:

$$\text{Species AB or B standarized} = \frac{\text{AB or B (Species sampled)}}{\left(\text{Speed}\left(\frac{\text{m}}{\text{s}}\right) \times SBW(m) \times HD(s)\right)} \times 10000$$

Where SBW is the mean distance between trawl wings which was provided by fishermen and HD is the haul duration.

With the Primer 6.1.2 statistical program (Clarke and Gorley 2006), discard abundance by species and hauls were square-root transformed, and their BrayCurtis similarity matrix was calculated. From this similarity matrix, a multidimensional scaling (MDS) plot was generated to visualize the ordination pattern between discards of the 23 hauls analysed.

Table 1. Fishing grounds depth characteristics

Fishing grounds depth characteristics	Capets	Fluviana	Las 40	Garotes	Malica	Planassa
Depth min (m)	70	93	83	54	195	85
Depth max (m)	113	144	102	107	493	530
Depth range (m)	42	51	19	52	298	444

Table 2. Average (Av) biomass of catch fractions for each fishing grounds studied.

Catch fractions (kg/ha)	Capets	Fluviana	Las 40	Garotes	Malica	Planassa
Av. total catch	3.93	7.44	6.66	7.53	2.66	8.22
Av. commercial catch	1.27	1.42	1.79	1.68	1.97	1.83
Av. Regulated discard	0.36	0.13	0.51	3.54	0.14	0.30
Av. Unregulated. discard	2.31	5.90	4.37	2.31	0.56	6.09
Av. Total discard	2.66	6.02	4.88	5.85	0.69	6.39

Table 3. Similarity discard analysis SIMPER taking fishing ground as factor. It showed average similarity between hauls (Av similarity), and regarding species: average abundance in individuals per hectare (Av.Ab), average similarity contribution (Av.Sim), average similarity divided per standard desviation (Av.Sim/SD), Similarity contribution in percetage (C) and accumulated similarity contribution in percentage (Cum) to the five species with the greatest contribution to similarity into each fishing ground.

	Av.Ab (ind/ha)	Av. Sim	Av.Sim/SD	C %	Cum %
LAS 40-CAPETS					
Av. similarity: 39.54					
Ophiura texturata	4.02	6.11	2.45	15.46	15.46
Spicara smaris	1.52	2.8	4.5	7.08	22.54
Echinaster sepositus	1.29	2.07	4.27	5.24	27.78
Echinus melo	1.2	1.93	2.83	4.88	32.66
Boops boops	1.49	1.72	2.84	4.35	37.01
PLANASSA					
Av. similarity: 26.65					
Leptometra phalangium	19.1	5.77	1.15	21.65	21.65
Gracilechinus acutus	2.75	2.31	0.88	8.66	30.31
Capros aper	3.71	1.62	0.9	6.09	36.4
Echinus melo	2.61	1.32	0.89	4.95	41.35
Plesionika heterocarpus	3.39	1.15	0.41	4.31	45.67
FLUVIANA					
Av. similarity: 15.82					
Leptometra phalangium	45.39	6.54	0.83	40.07	40.07
Scyliorhinus canicula	2.71	1.97	2.55	12.43	52.5
Echinus melo	4.63	1.92	1.59	12.15	64.65
Spicara smaris	1.26	0.96	1.59	6.08	70.73
Calliactis parasitica	1.04	0.72	0.58	4.55	75.29
MALICA					
Av. similarity: 57.90					
Nephrops norvegicus	1.93	8.29	3.32	14.33	14.33
Scyliorhinus canicula	1.62	6.63	1.57	11.46	25.78
Phycis blennoides	1.15	5.81	4.59	10.04	35.82
Arnoglossus rueppelli	0.99	4.65	5.44	8.03	43.85
Trigla lyra	1.16	3.72	1.56	6.43	50.28
GAROTES					
Av. similarity: 33.11					
Boops boops	6.54	24.01	-	72.52	72.52
Pagellus erythrinus	1.21	3.7	-	11.17	83.69
Echinaster sepositus	0.56	2.14	-	6.45	90.14
Mullus barbatus	0.36	1.31	-	3.95	94.1
Spicara smaris	3.35	1.24	-	3.74	97.84

After MDS, similarity percentage (SIMPER) analysis was carried out with the non-transformed matrix to determine the relative contribution that discard species made to the similarity among hauls using fishing ground as a factor. Due to the protection figure of maerl, a deeper analysis was carried on one fishing ground with maerl presence, where the average abundance of hauls by species was calculated.

The seasonal size distribution of the regulated discard species was represented graphically with the R 3.4.3 statistical program (R Core Team 2017) to summarize it both temporally and spatially.

VMS together with GT data of 28 trawlers from Blanes active between 2012 and 2014 were used to estimate the spatial and seasonal distribution of fishing effort. The information from VMS data does not indicate whether a vessel is fishing, so a speed filter was applied to raw data taking into account only VMS positions with trawl speeds of less than 4 knots (Demestre et al., 2015; Martín et al., 2014). Duplicated positions were deleted, and then filtered and unduplicated VMS data sets were used to represent the fishing effort distribution on a grid with a cell size of 1 km2, which offers a good resolution for the spatial characteristics of this fishery.

The fishing effort in each cell was estimated as follows:

$$Fishing\ effort\ = \sum NVMSi\ \times GTi$$

where NVMSi is the number of VMS points of each vessel per cell in a specific month and GTi is the GT value of each vessel. Both filtering and estimation were performed using the software QGIS 2.10.0 (QGIS 2015).

Finally, to study the most relevant links between fishing effort and regulated discards, the abundance and biomass of species with MCRS was calculated at particular fishing grounds and months and VMS data was plotted for these months and fishing grounds.

3. Results

3.1 Catch characterization

A total of 45 species were found in the commercial catch, and 15 regulated species and 171 non-regulated species were found in the discards. Table 2 shows the average biomass for each catch fraction from the fishing grounds studied.

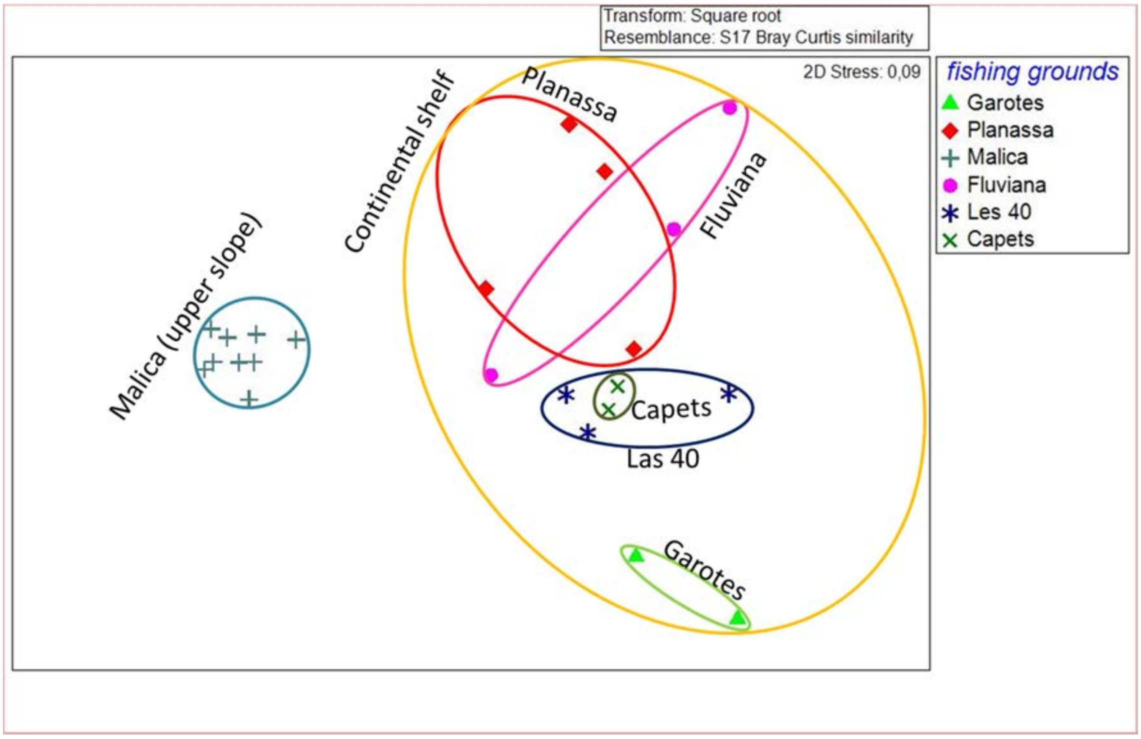

Fig. 2. – Discard MDS analysis; hauls and their occupied space are shown by fishing ground.

3.2 Total discard characterization

The MDS discard analysis shows a clear difference between continental shelf and upper slope hauls. Garotes and Malica were separated from the other fishing grounds (Fig. 2). On the other hand, Planassa and Fluviana shared some space, and Capets was within the area occupied by Las 40. Due to the spatial overlap and the strong connection between Capets and Las 40 in the MDS analysis, it was decided to jointly analyse these two fishing grounds for the rest of the work.

In the SIMPER discard analysis, *Echinus melo* had an important presence in Las 40-Capets, Planassa and Fluviana, contributing 12.15% of the similarity among Fluviana samples (Table 3). A noteworthy finding was that *Leptometra phalangium* explained more than 40% of the similarity at Fluviana and more than 20% of the similarity at Planassa.

Boops boops explained more than 70% of the similarity at Garotes, where commercial species such as *Mullus barbatus* or *Pagellus erythrinus* were always discarded as well. Finally, *Nephrops norvegicus* was the discarded species with the highest percentage of similarity to Malica (14.33%).

Table 4. Species abundance to Garotes hauls and his average (Av. Garotes), expressed in Individuals per hectare.

Species	Garotes 1	Garotes 2	Av. Garotes
Boops boops	38.77	46.83	42.80
Maerl rodoliths	43.56	0	21.78
Spicara smaris	40.80	0.10	20.45
Echinus melo	0	9.50	4.75
Octopus vulgaris	3.68	0	1.84
Pagellus erythrinus	0.92	2.14	1.53
Trachurus picturatus	2.61	0	1.30
Antedon mediterranea	0	2.38	1.19
Ophiotrix fragilis	0	2.38	1.19
Scomber scombrus	2.19	0.03	1.11

Species abundance at Garotes showed that the average abundance of maerl rhodoliths was one of the largest, with 21.78 ind. ha–1 (Table 4). The presence of maerl rhodoliths was located exclusively in the area corresponding to one of the two hauls carried out over a depth range of 54 to 70 m with rhodolith abundance of 43.56 ind. ha–1. Other abundant species in the discards of the Garotes fishing ground were *Boops boops* and *Spicara smaris*.

3.3 Regulated discard characterization

From the total hauls analysed, we observed 15 discarded regulated species: 9 regulated by MCRS and 6 regulated locally by the Spanish or the Catalan government (Table 5). These species include 12 fish, two crustaceans and one cephalopod.

The locally regulated species *Boops boops* was the most discarded species, with a total of 58.21% abundance, well above the discarded percentage of other species, among which only *Trisopterus capelanus* and *Nephrops norvegicus* exceeded 5%. *Merluccius merluccius*, *Lophius budegassa* and *Trachurus trachurus* were discarded in all fishing grounds except one.

In Garotes, species regulated by MCRS such as *Pagellus erythrinus*, *Mullus barbatus* or *Pagellus bogaraveo* were discarded, although with a percentage of abundance much lower than *Boops boops*, which was discarded in 87.45% of cases. As in Garotes, the most discarded species in Las 40-Capets was *Boops boops*, which, like *Trachurus trachurus*, exceeded 30% of discarded abundance at this fishing ground. On the other hand, in Planassa, *Micromesistius potassou*, *Merluccius merluccius* and *Pagellus bogaraveo* were the most discarded

Table 5: Abundance (ind/ha) and biomass (g/ha) at each fishing ground of discard species regulated by article 15 and species with local regulations, where Ab = Abundance, %Ab = abundance percentage, B = Biomass and %B = Percentage of Biomass.

		Garotes				Las 40-Capets				Planassa				Fluviana				Malica				Total			
		Ab	% Ab	B	%B	Ab	% Ab	B	%B	Ab	% Ab	B	%B	Ab	% Ab	B	%B	Ab	% Ab	B	%B	Ab	% Ab	B	%B
Art. 15 CE	*M. merluccius*	0	0	0	0	0.37	3.73	19.9	4.52	1.22	17.1	12.1	5.81	1.81	18.1	10.6	4.30	0.22	3.55	5.41	5.12	0.72	4.42	9.60	1.06
	M. barbatus	0.13	0.26	3.24	0.09	0	0	0	0	0.24	3.42	10.43	4.99	1.38	13.8	27.5	11.2	0	0	0	0	0.35	2.13	8.24	0.91
	P. bogaraveo	0.05	0.11	3.19	0.09	0.47	4.83	24.9	5.66	0.72	10.1	40.1	19.2	0.32	3.15	28.8	11.7	0.09	1.49	8.42	7.97	0.33	2.02	21.1	2.32
	P. erythrinus	1.53	3.13	84.54	2.39	0.54	5.57	33.5	7.61	0	0	0	0	0	0	0	0	0	0	0	0	0.41	2.53	23.6	2.60
	S. scombrus	1.11	2.27	77.21	2.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22	1.36	15.4	1.70
	T. picturatus	1.30	2.67	89.01	2.51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26	1.59	17.8	1.96
	T. trachurus	0.02	0.04	0.60	0.02	2.95	30.1	108.5	24.7	0.74	10.3	23.6	11.3	0.08	0.79	3.78	1.54	0	0	0	0	0.76	4.62	27.3	3.01
	N. norvegicus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.27	69.8	46.1	43.7	0.85	5.21	9.23	1.02
	P. longirostris	0	0	0	0	0	0	0	0	1.21	17.0	6.00	2.87	0	0	0	0	0.76	12.4	5.52	5.23	0.39	2.40	2.30	0.25
Local regulations	*T. capellanus*	0	0	0	0	0.52	5.29	6.33	1.44	0.27	3.79	11.7	5.62	3.54	35.4	13.9	5.66	0	0	0	0	0.87	5.29	6.40	0.70
	M. potassou	0	0	0	0	0	0	0	0	2.46	34.5	97.7	46.8	0	0	0	0	0.32	5.26	10.6	10.1	0.56	3.40	21.7	2.39
	L. budegassa	0.05	0.11	4.01	0.11	1.06	10.9	55.8	12.7	0.17	2.39	3.65	1.75	0	0	0	0	0.41	6.64	13.4	12.7	0.34	2.07	15.4	1.69
	L. piscatorius	0	0	0	0	0.46	4.71	32.96	7.49	0.11	1.49	3.47	1.66	1.42	14.2	16.0	6.51	0.01	0.24	0.25	0.24	0.40	2.44	10.5	1.16
	B. boops	42.8	87.7	2726	77.0	3.42	34.9	151	35.9	0	0	0	0	1.45	14.6	145.3	59.1	0	0	0	0	9.53	58.2	605.9	66.7
	O. vulgaris	1.84	3.77	552	15.60	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0.62	15.8	15.0	0.38	2.29	113.6	12.5

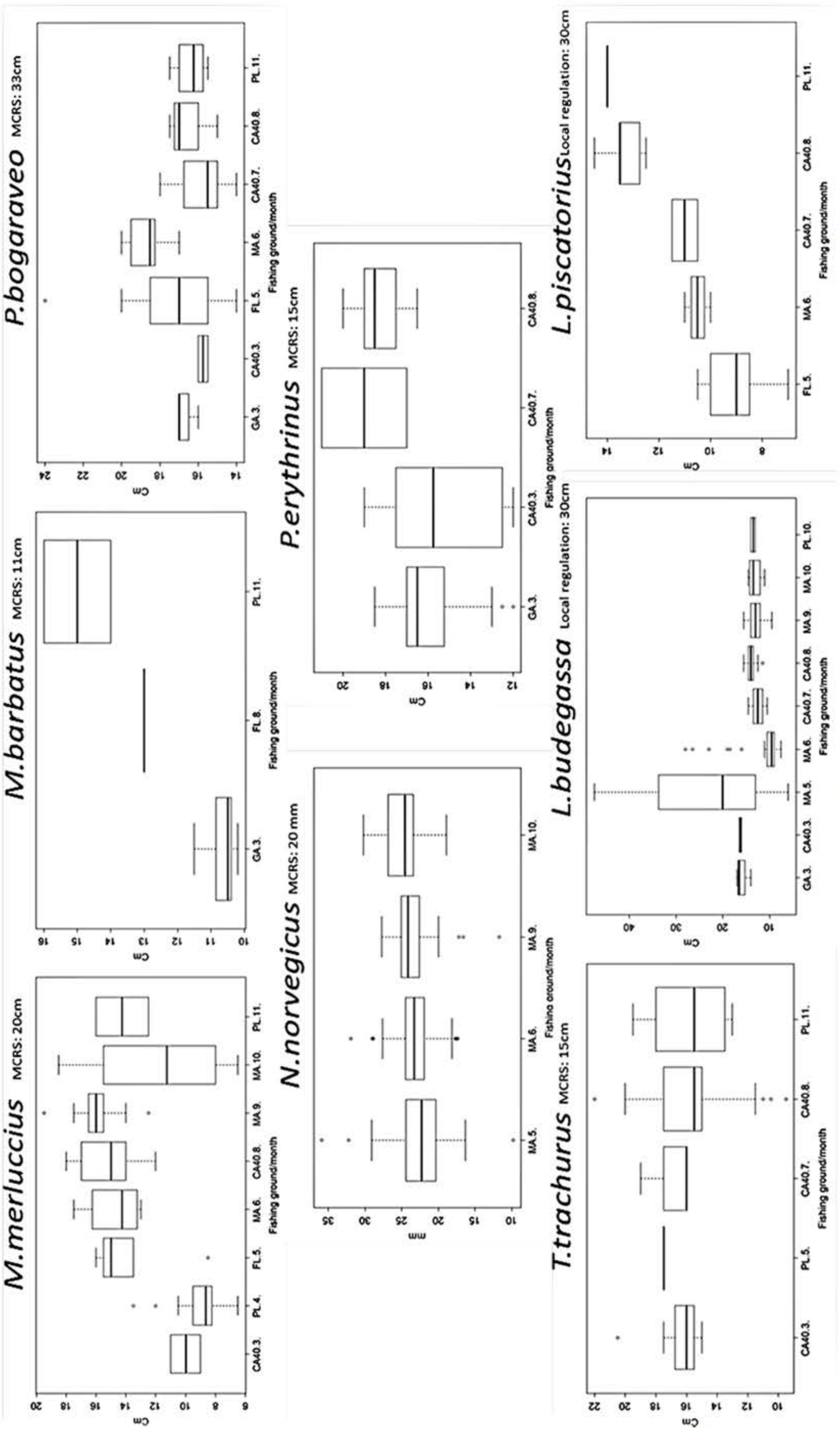

Fig. 3. – Monthly (in number) size distribution of the regulated species discarded from each fishing ground (Ga, Garotes; Pl, Planassa; Fl, Fluviana; CA40, Las 40-Capets; MA, Malica).

Finally, it is noteworthy that the most discarded species in Malica was *Nephrops norvegicus*, with 69.83% abundance and 43.67% biomass (Table 5). Regarding the size of the discarded regulated species, Figure 3 shows the size ranges of the eight species that were important in the study area because of their commercial interest. Only the genus *Lophius* is regulated at the local level. *Pagellus bogaraveo* was discarded in all fishing grounds due to its small size, and *Lophius piscatorius* and *Merluccius merluccius* were discarded for their small size in all fishing grounds except Garotes, where neither were discarded (Fig. 3). In addition, the fraction of *Lophius piscatorius* discarded grew over time, while *Merluccius merluccius* was discarded during all sampling months.

Nephrops norvegicus was discarded exclusively in Malica and showed an increase in the size of discarded individuals over time. *Mullus barbatus* and *Lophius budegassa* also showed an increase in size over time.

3.4 Fishing effort dynamics

From 2012 to 2014 at the fishing grounds adjacent to Blanes port, trawl fleet dynamics were described, and the fishing effort was estimated per month for all fishing activity areas (Fig. 4).

The fishing ground Malica, located on the upper slope, endured intense fishing activity throughout the year, although fishing effort increased specifically in May and June. In Planassa and Fluviana, there was a fairly continuous fishing effort throughout the year, although it was less intense than in Malica. In addition, Fluviana was the fishing ground least frequently exploited by the fleet. Finally, Garotes, Capets and Las 40 showed a clear seasonal variation in fishing effort, with practically no fishing effort during some months of the year in Garotes. However, in September, there was a sudden increase in fishing effort at Garotes, which continued until December and then progressively decreased until April. Finally, Capets and Las 40 showed low but continued fishing effort throughout the year, except from July to November, when it increased significantly.

3.5 Link between fishing effort dynamics and regulated discard

The fishing effort at Las 40-Capets was significantly lower in March than in July and August (Fig. 5). This increase coincided with an increase in the regulated MCRS discard biomass, which was practically double that in March (Table 6). At the species level, it occurred with practically the same pattern. Most of the regulated species were discarded in greater numbers and biomass in July and August. This was the case for the target species *Pagellus bogaraveo*, of which only 0.004 g ha–1 were discarded in March, while in July and August, 41.47 g ha–1 were discarded.

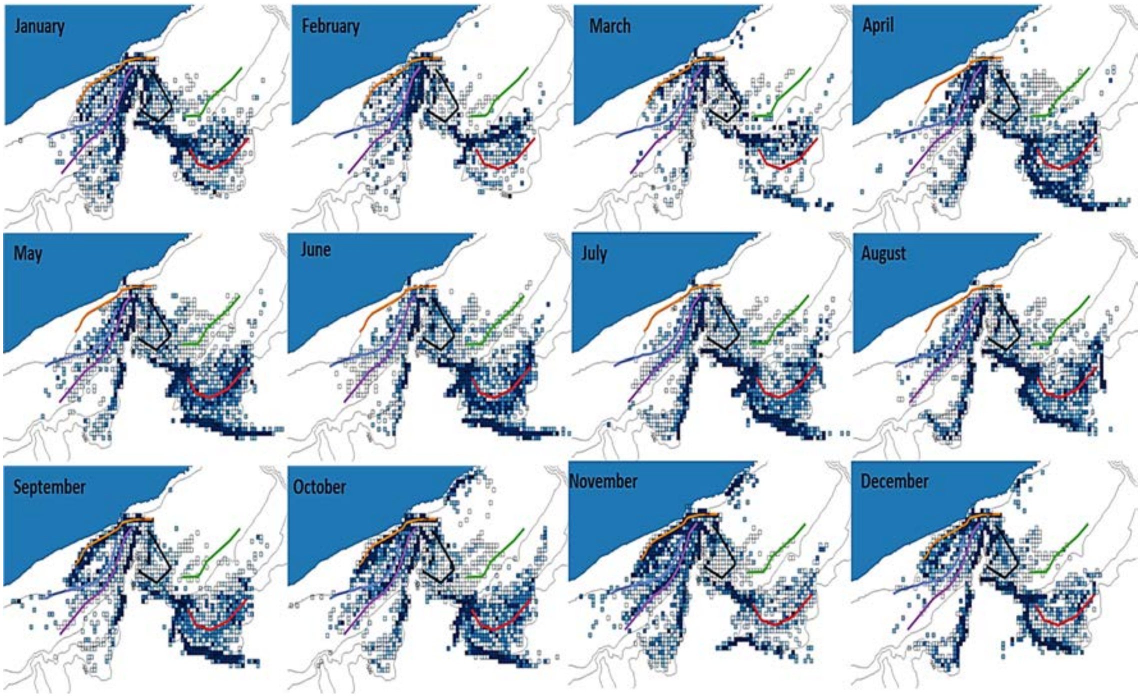

Figure 4- Monthly Fishing effort estimates of the Blanes trawl fleet (2012 – 2014) and the locations of the fishing grounds studied (red = Malica, Green = Fluviana, Black = Planassa, purple = Las 40, light blue = Capets and orange = Garotes).

In Malica, the total average discard biomass and abundance of regulated species was higher in May and June than in September and October (Table 7). For example, an average of 56.24 g ha–1 of *Nephrops norvegicus* was discarded in May and June, while an average of 19.44 g ha–1 was discarded in September and October, coinciding with a decrease in fishing effort in these last two months (Fig. 6).

4. Discussion

The present work has analysed the captures of commercial trawl vessels, emphasizing the links between the discard fraction, specific species affected by the new European regulation on landing obligations and by local regulations, and the seasonal and spatial distribution of the fishing effort of the Blanes trawl fleet. Our final goal was to link these two types of information to propose measures that can help minimize or avoid unwanted catches.

Fishermen develop dynamic fishing strategies as an adaptive response to changes in resource abundance, environmental conditions and market or regulatory constraints (Martín et al., 2014). The Blanes fleet fishing effort showed two different behaviours: a continuous fishing effort in the canyon and upper slope zones, which corresponds to specialist behaviour on fishing grounds with *Aristeus antennatus* and *Nephrops norvegicus* as the target species; and a discontinuous fishing effort on most of the continental shelf

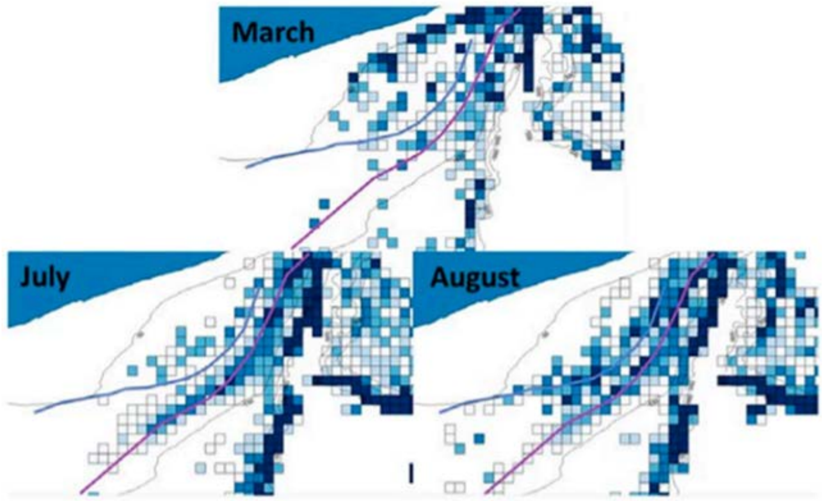

Fig. 5. – Fishing effort dynamics detail in Las 40-Capets for March, July and August.

Table 6. – Average biomass (g ha^{-1}) and abundance (ind. ha^{-1}) of species affected by the landing obligation for the months shown in Figure 5.

Las 40-Capets	Av. March		Av. July-August	
	Abundance	Biomass	Abundance	Biomass
Merluccius merluccius	0.41	3.68	0.34	30.72
Pagellus bogaraveo	0.09	0.004	0.73	41.47
Pagellus erythrinus	0.92	46.47	0.29	24.81
Trachurus trachurus	1.97	78.6	3.6	128.49
Total	3.39	128.75	4.96	225.49

fishing grounds, which corresponds to the generalist behaviour where there were several target species, such as *Merluccius merluccius*, *Mullus spp*., or *Lophius spp*. The knowledge of these dynamics is fundamental for the effective management of fisheries (Salas et al., 2004). Similar to the findings of previous works on the Blanes trawl fleet (Sanchez et al., 2004; Tsagarakis et al., 2014), this specialist or generalist behaviour was related to the discard amount, which was significantly higher on the continental shelf than on the upper slope (Table 2). Discard heterogeneity was also related to higher discard amounts, which were predominantly located on the continental shelf, with a similarity of between 15% and 40% (Table 3), while the most homogeneous fishing ground, located on the upper slope, showed less discard and an average similarity close to 60%.

Knowledge on the distribution of fishing activities should be followed by the characterization of the fished habitats (Demestre et al., 2000). Discard analysis by species revealed the existence of two especially productive but vulnerable Mediterranean habitats.

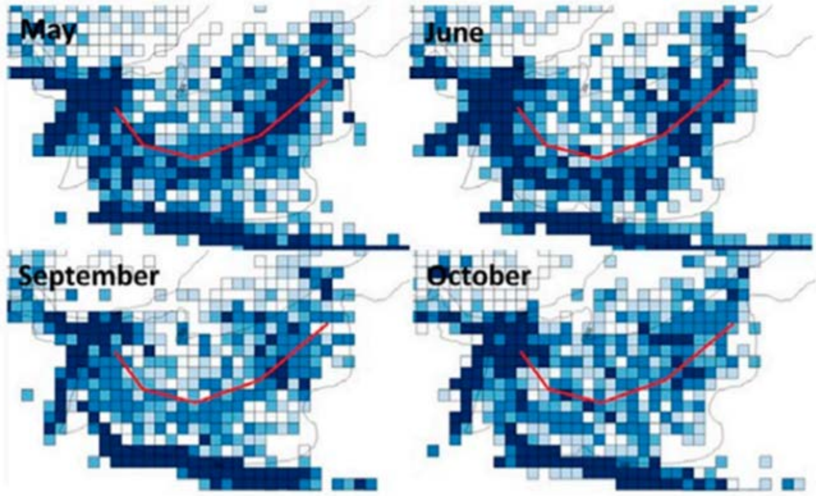

Fig. 6. – Fishing effort dynamics detail in Malica for May, June, September and October.

Table 7. – Average biomass (g ha^{-1}) and abundance (ind. ha^{-1}) of species affected by the landing obligation for the months shown in Figure 6.

Malica	Av. May-June		Av. September-October	
	Abundace	Biomass	Abundance	Biomass
Merluccius merluccius	0.07	1.35	0.52	10.14
Pagellus bogaraveo	0.14	12.62	0	0
Nephrops norvegicus	5.12	56.24	2.57	19.44
Parapenaeus longirostris	0.98	6.77	0.31	2.27
Total	6.3	76.99	3.4	31.85

First, in Garotes, an area with maerl rhodoliths was found. This could indicate that in the past, there was an active maerl bed that over time has been degraded as a result of fishing pressure. Although maerl is protected in Annex I of the Habitat Directive (EU Dir. 92/43/EEC), fishing pressure is still exerted on maerl habitat, here and in other Mediterranean areas (Demestre et al., 2017). In the western Mediterranean, maerl bottoms can reach 90 or 100 m depth (Basso 1996), and in Garotes, rhodoliths were found in the hauls carried out at lower depths, between 54 and 70 m (Table 4), where the fishing effort intensity was very low for five months out of the year (Fig. 4). However, there was a constant fishing effort in deeper areas of this fishing ground, between 80 and 107 m depth, where maerl rhodoliths were not found. It is possible that the maerl, due to its vulnerability to trawling (De Juan et al., 2013; Barberá et al., 2012), disappeared completely from deep areas of Garotes, surviving only in areas with lower fishing pressure. Second, areas with *Leptometra phalangium* crinoid aggregations were also found in two adjacent fishing grounds, Planassa and Fluviana. These fishing grounds showed the largest biomass of unregulated discards (Table 2), high heterogeneity (Table 3) and moderate but continuous fishing effort throughout the year. In the three fishing grounds where commercial species below the legal size (such as *Merluccius merluccius,* *Lophius spp., and Pagellus spp.*) were captured, catches showed that they function as nursery areas, as is confirmed in other studies (Hall-Spencer et al., 2003; Steller et al., 2003; Colloca et al., 2004).

A high similarity between the Las 40 and Capets fishing grounds is suggested by the close association of their hauls in MDS space (Fig. 2). Their discards were mainly composed of echinoderms such as *Ophiura texturata* and *Echinus melo* and the locally regulated fish *Boops boops*, but juveniles of several commercial species, such as *Merluccius merluccius* and *Pagellus bogaraveo*, were also found (Fig. 3), suggesting that these fishing grounds could also function as nursery areas for some commercial fish species.

Although in a higher bathymetric range, a previous study carried out in the Catalan Sea (Maynou and Cartes 2000) revealed a *Nephrops norvegicus* incidence of 1.8 ind. ha–1 for the total catch. In our work *Nephrops norvegicus* discard had a considerable incidence in Malica, where with 4.27 ind. ha–1 it was the most discarded species, mainly due to its small size. This commercial species is regulated by an MCRS and avoiding the capture of small individuals is imperative to improve fishery management (Méhault et al., 2016). In addition, Norway lobster showed good survival potential in several studies (Campos et al., 2015; Méhault et al., 2016), and this species could be exempt from the landing obligation because of its high survival (Article 15 of EU Reg. 1380/2013). Sorting methods to improve the survival of the discards of this species in the Mediterranean should be adopted, such as sorting tables to expedite discard activities (García-de-Vinuesa et al., 2017).

The discarding behaviour of the Blanes trawler fleet is related to the biology of some species regulated by MCRS. The period of greatest reproductive activity of many Mediterranean commercial fish species, such as *Merluccius merluccius, Mullus barbatus, Mullus surmuletus, Pagellus bogaraveo, Pagellus erythrinus* and *Trachurus trachurus*, occurs between late spring and late autumn (Recasens et al., 2008; Tsikliras y Stergiou 2014; Carbonara et al., 2015), and there was a significant increase in fishing effort in autumn and winter at several of the continental shelf fishing grounds studied, corresponding with the season of recruitment of these animals. This was the case for Garotes, where the fishing effort increased from September to April and discarding increased significantly in March for *Mullus barbatus, Pagellus erythrinus* and *Pagellus bogaraveo* (Fig. 3) below the MCRS. In Las 40 and Capets, two species of the genus *Pagellus* plus *Merluccius merluccius* and *Trachurus trachurus* were discarded mainly because they did not reach the MCRS (Fig. 3), and the total discarded biomass of these regulated species at the end of summer was practically double that in March (Table 6). On the other hand, in Malica, the smallest individuals of *Nephrops norvegicus* were discarded almost three times more often between May and June, when fishing effort increased, than in September and October (Table 7). Finally, although there was no significant seasonal change in fishing effort at fishing grounds with crinoid aggregations, MCRS-regulated species such as *Mullus barbatus, Merluccius merluccius*, *Pagellus bogaraveo* and *Trachurus trachurus* were discarded, the last three below their MCRS. Due to the costs in time and money that the landing obligation entails, one of the expected positive consequences can be the increased interest of fishermen in avoiding areas where unwanted species are caught, thus improving fishing efficiency (Vilela y Bellido 2015).

Species regulated at the local level that are also commercially important include those of the genus *Lophius spp*. which comprise two target species in the region that were discarded in all the fishing grounds studied (almost always under the local minimum legal size) and *Micromesistius poutassou, Trisopterus capelanus* and *Octopus vulgaris*, which are accessory species to the Blanes trawl fleet. *Boops boops* was the only non-commercial regulated species that we found, and it was the most discarded species.

Conclusions

The joint study of catch focusing especially on the discard fraction and fishing effort dynamics provides a useful tool for improving the management of trawling fisheries and particularly for avoiding unwanted catches. The presence of maerl in Garotes together with the large discard rates and the obligation to land six species affected by MCRS suggests that this area could be a good candidate for establishing a permanent no-take zone to avoid the problem of unwanted catches and prevent further habitat degradation. Additionally, it is demonstrated that, as in Garotes, fishing effort on Las 40 and Capets increased during recruitment months for commercial species affected by the landing obligation. Thus, carrying out seasonal closures in these fishing grounds is recommended, and although no seasonal pattern was found in the behaviour of the fleet in fishing grounds with crinoid aggregations, seasonal closures could be carried out during the recruitment season of discarded species regulated by MCRS such as *Merluccius merluccius and Mullus barbatus* or species regulated locally such as *Lophius spp*. to avoid unwanted catches. These closures would be more beneficial in late spring or summer, but not in February, as has already been adopted in the area by internal agreement among the fishermen. Also, *de minimis* exemption could be applied for hake and red mullet, up to a maximum of 7% of the total annual catches in 2018 and 6% in 2019 (EU Reg. 2017/86) in all fishing grounds, but this would only be a shortterm solution.

Finally, in Malica, the possibility of reducing fishing effort in the months in which smaller individuals of *Nephrops norvegicus* were discarded should be studied, particularly in the months of May and June.

Acknowledgements

This work was funded by the research project MINOUW (H2020-SFS-2014-2) from the European Commission (contract nº 634495). We also acknowledge the help of the vessels' crew during sampling and the data provided by MAGRAMA, which were indispensable for meeting the objectives of this work.

Capítulo 2a

Ecological importance of survival of unwanted invertebrates discarded in different NW Mediterranean trawl fisheries

Ecological importance of survival of unwanted invertebrates discarded in different NW Mediterranean trawl fisheries

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Publicado: Scientia Marina 82S1 November 2018, 189-198

https://doi.org/10.3989/scimar.04784.28A

Summary: There is currently very little information on the survival of discards of unwanted and unregulated catches of invertebrates after the stresses caused by capture. A great number of the unregulated invertebrate species form the basis of essential fish habitats for important fisheries resources such as hake, red mullet and cuttlefish. Thus, data on their survival after discarding may help to interpret the role of these species within the benthic ecosystems. Furthermore, descriptor 6 of the Marine Strategy Framework Directive (EU Directive 2008/56/E) foresees maintaining sea floor integrity at a level that ensures that the structure and functions of the ecosystems are safeguarded, and Article 7(d) of the Common Fisheries Policy (EU Reg. 1380/2013) foresees the implementation of management measures for fishing with low impact on the marine ecosystem and fishery resources. Survival measurements by direct recovery of tagged discarded species are not effective in bottom trawl fisheries, for which alternative studies such as semi-quantitative measures obtained on board prior to discarding can be considered as appropriate for mortality estimation. The present work assessed the survival of unwanted species using a semi-quantitative assessment on the deck of trawlers and at the laboratory for a period of 96 hours in two Mediterranean areas (the Catalan coast and the Ligurian and Northern Tyrrhenian seas). A high number of discarded invertebrates showed a high percentage of survival (>70%) in both assessments. The results can be used to provide information that can help to achieve higher survival levels of discarded specimens and enhance the productivity of fishing grounds by increasing the health of benthic ecosystems.

Keywords: discard survival; invertebrates; mortality estimation; vitality levels; trawl fishery; Mediterranean.

Importancia ecológica de la supervivencia de invertebrados no-deseados descartados en distintas pesquerías de arrastre del Mediterráneo nor-occidental

Resumen: Actualmente, hay muy poca información sobre la supervivencia del descarte de los invertebrados no-deseados y no-regulados después del stress de la captura. Un gran número de especies de estos invertebrados son básicas para los hábitats esenciales de importantes recursos pesqueros como la merluza, el salmonete o la sepia. Por lo tanto, información sobre su supervivencia al ser descartados pueden ayudar a interpretar el papel de estas especies dentro de los ecosistemas bentónicos. Además, el punto 6 de la Directiva Marco de Estrategia Marina (MSFD, EU Directive 2008/56/E) prevé mantener la integridad del fondo marino a un nivel que garantice la protección de la estructura y de las funciones de los ecosistemas, y el artículo 7 (d) de la Política Pesquera Común (PPC EU Reg. 1380/2013) prevé la implementación de medidas de gestión para la pesca, que tengan bajo impacto tanto en el ecosistema marino como en los recursos pesqueros. En el caso de las pescas de arrastre de fondo, no es efectiva la estimación de la supervivencia a partir del método directo de captura-recapture de las especies del descarte marcadas, por lo que los estudios alternativos, como las medidas semicuantitativas obtenidas a bordo antes del descarte, pueden considerarse una estimación de la mortalidad apropiada. El presente trabajo evaluó la supervivencia del descarte de especies no-deseadas utilizando una Evaluación Semicuantitativa (SQA) mediante dos estudios: uno sobre la cubierta de los arrastreros y el otro en laboratorio durante un período de 96 horas, en dos áreas del Mediterráneo, las costas Catalanas y en los mares de Liguria y del Tirreno Norte. Los resultados mostraron en ambos estudios, que un alto número de invertebrados descartados tenía un alto porcentaje de supervivencia (>70%). El propósito de estos resultados es proporcionar información que puede ayudar a alcanzar niveles de supervivencia más altos de los individuos descartados. Al mismo tiempo, se espera que con esta mejora se consiga potenciar la productividad de los caladeros al aumentar la salud de los ecosistemas bentónicos.

Palabras clave: supervivencia del descarte; invertebrados; estimación de mortalidad; estados de vitalidad; arrastre, Mediterráneo.

1. Introduction

Mediterranean fisheries are characterized by a high rate of unwanted catches and a great number of marine organisms that are discarded at sea (Lleonart 2015; Tsagarakis et al., 2014). One of the fishing methods that produces most discards is otter bottom trawling, which is also one of the least selective fishing gears. The discards include both species with non-commercial value and marketable species that are undersized or of low value. Technical regulations, such as the introduction of the 40-mm square mesh or the 50-mm diamond mesh in the cod-end (EC 1967/2006) can reduce discards to some extent, but cannot solve the impacts of bottom trawling on habitats and benthic communities. The investigated areas were the Catalan coast, corresponding to FAO division 37.1.1, Geographical SubArea 6 (GSA06), and the Ligurian and northern Tyrrhenian seas, corresponding to FAO division 37.1.3, Geographical Sub-Area 9 (GSA09), both comprising chronically exploited fishing grounds. In the last ten years the demersal fisheries carried out mainly by bottom trawl fleets in the two areas accounted for about 40% of the total landings and 70% of the economic value (STECF 2016).

A large fraction of this discarded biomass (30%- 50% of the total biomass caught) is composed of species of commercial interest (small-sized or damaged specimens), while the remaining fraction is composed of species with low or no economic value (Machias et al., 2001; Sánchez et al., 2004, 2007). Furthermore, trawl fleets operate in a great variety of soft habitats (e.g. muddy-sand, sandy-muddy, mud, sandy-gravel, sand), so discards are characterized by extremely high species diversity with a high percentage of non-commercial species, some of which are macroinvertebrates (echinoderms, crustaceans, poriferans, ascidians, cnidarians, bryozoans, bivalves and gastropods). In many cases the discarded species belong to sensitive benthic habitats, such as maerl or crinoid beds.

The impact of bottom trawling on benthic habitats and communities and demersal species is little known. The impact depends on the fishing activity (Martín et al., 2014) and can create changes in the ecological functioning of benthic components that have important repercussions on the exploited populations (de Juan et al., 2007; Frid 2011; Hewitt et al., 2008).

The European Marine Strategy Framework Directive (EU 2008/56/E) encourages member states to move towards an ecosystem-based fishery management in order to protect the goods and services that marine ecosystems provide. Therefore, it is important to take into account the link between benthic communities and habitats and fisheries resources, because a great number of ecological interactions may be adversely impacted by fishing. The capture of benthic invertebrates and their discarding at sea will impact benthic habitats to a certain degree, depending on the post-release survival of each species. The survival of habitat-structuring invertebrates, such as crinoids and echinoderms, can help to maintain the good status of the essential fish habitats where the most important commercial resources, such as European hake, red mullet, spiny lobster and cuttlefish, use them as areas of nursery, recruitment or growth (Abella et al., 2008; Massi et al., 2016).

There is currently very little information on the survival of unwanted and unregulated invertebrates after the stresses of being captured, handled and discarded. The specific biological characteristics make an organism more or less vulnerable to different stressors of the capture method and release process (de Juan and Demestre 2012). Other factors affecting the survival of released animals are related to the handling practices during the sorting and release processes and to the environmental conditions during capture, hauling on board and sorting, such as hypoxia and temperature (Bergmann et al., 2001; Giomi et al., 2008; Tsagarakis et al., 2017).

Some unwanted and unregulated invertebrates such as crinoids and ophiuroids form the basis of essential fish habitats for commercial species such as hake and red mullet. Robust information on discard survival after fishing and release to the seabed can improve the interpretation of the role of unregulated invertebrates on the benthos (Benoît et al., 2012).

The main objective of this paper was to estimate survival rates of invertebrates discarded from trawlers working in two northwestern Mediterranean areas, the Catalan coast and the Ligurian and northern Tyrrhenian seas. The study focused on unwanted invertebrates which belong to the unregulated species and are likely to continue to be released after capture. To estimate the vitality rates, a vitality assessment on the captured organisms was carried out under normal fishing activity of the trawl fleets in both selected areas. The approach was developed using a semiquantitative assessment (SQA) (ICES 2014) according to Benoît et al., (2012). Two different procedures of survival estimation were developed, considering first the survival on the deck of trawlers and second the long-term survival at the laboratory with captive observations. The survival rate of the discarded fraction in the trawl catch can be used to propose man agement based on better control of discards or spatial restrictions to trawling that may accompany specific management plans based on conserving the functionality and health of benthic ecosystems.

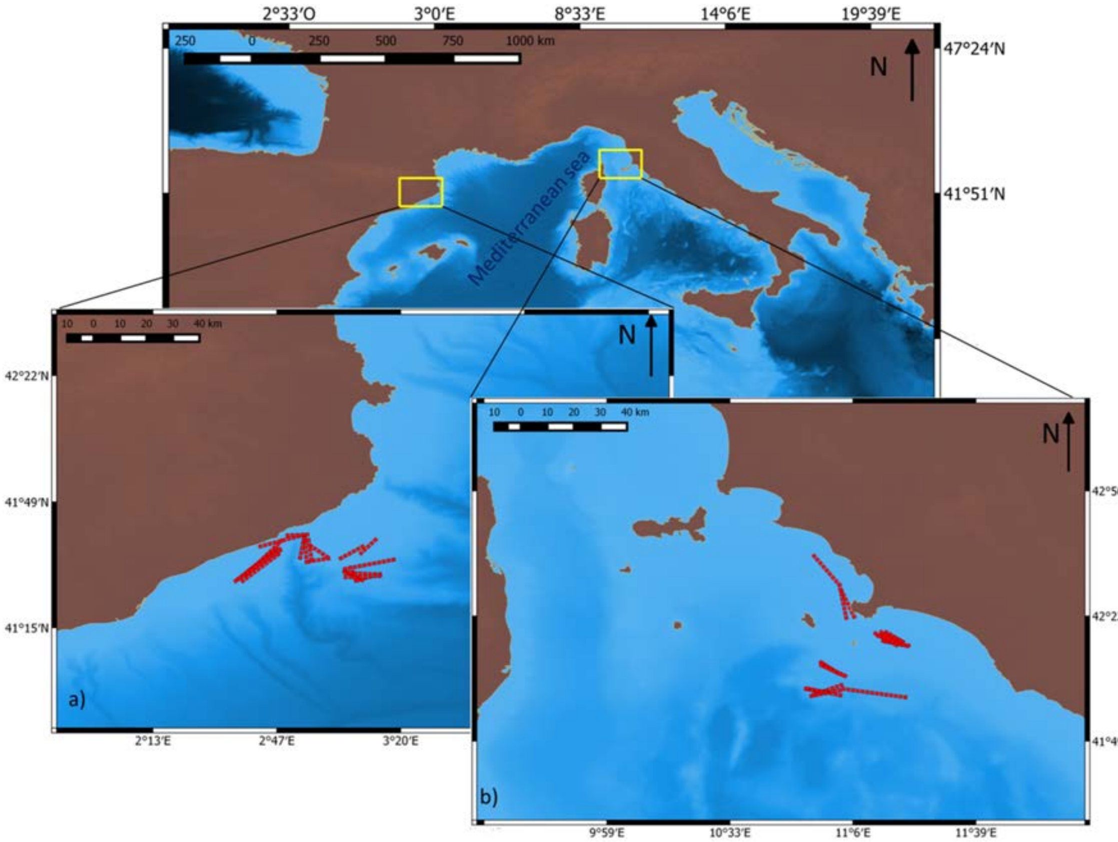

Fig. 1. – Study areas: A, Catalan coast; and B, Ligurian and northern Tyrrhenian seas. Red lines indicate hauls in the selected fishing grounds

2. Materials and methods

2.1 Study areas and sampling activities

The study was carried out in two NW Mediterranean trawl fishing areas, the Catalan coast (GSA 6), from March 2016 to February 2017, and the Ligurian and northern Tyrrhenian seas (GSA 9), from November 2016 to February 2017. Data were collected during fishing trips on board commercial vessels performed on a monthly basis.

Trawl sampling in the Catalan coast area was performed on board four different trawlers in five fishing grounds (Garotes, Las 40, Capets, Planassa and Malica) adjacent to the port of Blanes. The depth range was between 50 and 494 m, with a total of 23 hauls (Fig. 1A; Table 1). In the Ligurian and northern Tyrrhenian seas, 22 commercial hauls were carried out in a bathymetric range of 85-470 m in the Monte Argentario area (Fig. 1B; Table 1).

Table S1 of the Supplementary Material details the main characteristics and environmental data of each haul in the two selected areas. In both areas the average haul duration was about two hours.

At the end of each haul the trawl gear was retrieved on board and the cod-end was opened on the deck following the normal commercial fishing practices. After that, prior to sorting the catch into commercial and discard fractions, the net was shot for a new haul. Depending on the depth, this process took 10 to 25 minutes. During the fishing trips, there was no interference by the researchers on board with the habitual modus operandi of the fishermen in the daily fishing activity (position, duration, sorting, etc.) and the sorting processes of the catch, which lasted 20-30 minutes depending on the capture.

Table 1. General information on trawl sampling in the study areas.

Study area	Fishing ground	No Hauls	Min. depth	Max. depth	Target species
Catalan Coast CC (G16)	Las 40	3	85	120	Red mullet, monkfish, hake, Octopus and sea cucumber
	Capets	3	70	113	Red mullet, monkfish, hake, Octopus and sea cucumber
	Planassa	6	86	318	Red mullet, sea cucumber, hake and monkfish
	Garotes	2	55	107	Red mullet and pandora
	Malica	9	195	494	Norway lobster
Ligurian and northern Tyrrhenian Seas (LT) (G09)	Argentario	22	85	470	Hake, red mulle, horned octopus and deep- water pink shrimp

2.2 Survival experiments

The hauls considered for survival analysis were 4 on the Catalan coast and 19 in the Ligurian and northern Tyrrhenian seas (Supplementary material Table S1A). The average depth range was between 99 and 362 m on the Catalan coast and between 84 and 470 m in the Ligurian and northern Tyrrhenian seas. The hauls were carried out on both the continental shelf and the upper slope, with a standard deviation of 117.66 and 152.89 m, respectively. The complexity of the experiment forced us to limit the number of hauls. While the catch was being sorted manually on deck by the fishermen, in both areas the vitality of the unregulated, non-commercial invertebrates was assessed just before the species were discarded. The SQA (ICES 2014) was performed by means of indicators of state of vitality according to mobility, injuries and lesions suffered by the organisms due to the fishing activity. To estimate the vitality of each individual, a categorical assessment scale of four vitality levels (VL) was applied: 1 (excellent), 2 (good), 3 (poor) and 4 (dying or dead) (Benoît et al. 2012, ICES 2017). A detailed explanation of each VL is presented in Table 2.

Two approaches to performing the survival experiments were developed: i) direct survival estimation on deck and ii) survival estimation at the laboratory for a period of 96 hours. In both study areas the studied invertebrates are only captured by trawling. Because of the challenges of obtaining viable control samples with other gears, the individuals who were classified in excellent state of vitality (Table 1) at the start of the captive experiment (time T0, just as it was being released on deck) were taken as pseudo-controls for each haul (ICES 2014).

Table 2. Description of vitality levels of invertebrate organisms for a semi-quantitative assessment approach by groups of likely animals (From ICES 2014 and Demestre 2012)

Vitality Levels (VL)	Code	Crustaceans	Echinoderms (Ophiuroidea and Asteroidea)	Echinoderms (Echinoidea)	Mollusca	Sessile
Excellent	1	Continued movements. No external injury	Continued movement. N o external injury	Continued movement. No external injury	Continued movement. No external injury	Shape and size similar to its natural state. No external injury
Good	2	Weak movements; answers to the contact. No external injury or superficial cuts on the exoskeleton or antennas.	Weak movements; answers to the contact. No external injury or superficial cuts in limbs	Weak movements; answers to the contact. No external injury or superficial cuts in barbed	Weak movements; answers to the contact scraping the shell or moderate loss of tegument	Size and shape Moderately different from its natural state, cuts or abrasions moderate
Poor	3	Without apparent movement, but can move antennas or maxilipeds, loss of a member or deep cuts.	Without apparent movement, but can move tube feet. Cuts deep and loss of all or part of extremities	Without apparent movement, but can move tube feet; external injury and many cuts in barbed.	Without apparent movement, but can move tube feet, loss of parts of the shell or limbs.	Shape and size different to their natural state, cuts, abrasions, surface, serious, or loss of body parts.
Dying or dead	4	Without movement, does not respond to the contact.	Without movement, does not respond to the contact. Loss of central parts of the body	Without movement, does not respond to the contact or broken shell.	Without movement, does not respond to the contact, or broken shell.	Loss of central parts of the body.

2.3 Survival estimation on deck

In both areas the immediate survival on deck was estimated following the same methodology. For the selected species, as many individuals as possible were taken and one of the four VLs was assigned to each one using the SQA (Table 2). The selection process was carried out only during the first 30 minutes after opening the net on the deck, starting before the gear was shot for a new haul. It was done as quickly as possible to decrease as far as possible the time of air exposure on deck.

2.4 Survival at the laboratory

The long-term survival rate was estimated for 96 h to achieve a deeper knowledge of the actual survival of the invertebrates discarded. It was only performed in the Catalan coast area. To analyse survival at the laboratory, the individuals of the selected species were sampled from the last daily haul, just when the catch was laid on deck and prior to sorting, but only during the first 30 minutes, as in the previous case. The VL was assessed according to the SQA (Table 2). The four possible VLs were observed for each specimen, which were individually introduced in four white containers (one for each VL), with running sea surface water to avoid hypoxia. The maximum number of selected animals was that which could be introduced in each container without causing stress. A total of 324 individuals from 22 species of invertebrates (10 echinoderms, 8 crustaceans, 2 cnidarians and 2 ascidians) were sampled but only the 6 most abundant species were selected for this survival assessment.

Survival at the laboratory was estimated for 96 hours in an aquarium at the ICM laboratory by applying an SQA. A total of ten time survival observations (T) were carried out during the experiment (from T0 to T9). The first observation, time T0, just as animals were being released on deck, was executed on board. Individuals were selected for a maximum time of 30 minutes, and each one was introduced successively into the containers, as explained above. The second observation, T1 (6 h), was performed just before each individual was transferred to the aquariums at the laboratory. The individuals that were in VL 4 (dead or moribund) were removed to avoid contamination in aquariums, but were accounted for. The following eight observation times, from T2 (18 h) to T9 (96 h), were made on the specimens placed in the aquariums, with a periodicity of 12 h until the study had lasted for 96 h. The aquariums were divided into three sections for each VL, 1, 2 and 3, and no more than ten individuals were introduced per section. The time of the transport from the sea to the aquariums was a maximum of 2 hours and the animals were on the white plastic containers with oxygen pills during the whole transportation time.

The natural environment conditions were simulated in the aquariums through an open seawater circuit and water temperature was maintained between 13°C and 14°C, similar to the in situ temperature in the northwestern Mediterranean fishing grounds. The photoperiod was adapted to the natural luminosity with black canvas to dim the light. Controls of salinity, nitrates, nitrites and silicates were periodically performed. The whole process was carried out under food abstinence conditions.

2.5 Data analysis

The survival on deck was estimated by applying the survival index, which was calculated as the ratio between the number of specimens (VN) with a vitality level of 1 to 4 and the total number of discarded individuals (DN) and was expressed as a percentage. A Wilcoxon test between the exploratory variables recorded (Supplementary material Table S1) and the survival of invertebrates on deck for the first 30 min on board was carried out. The test analyses the relationship of each variable with survival, comparing the data related to live individuals (VLs 1, 2 and 3) with data of dead individuals (VL 4). Finally, if significant differences were observed between the variable and the survival, the group mean was calculated.

The Wilcoxon test was implemented in R 3.4.3 (R Core Team 2017). Because a seasonal sampling was not performed, variables related to seasonality such air and water temperatures were not taken into account. We therefore conducted the analysis only with Depth and Haul Time. To calculate survival rate for each experiment over 96 h, the Kaplan-Meier analysis was used (Kaplan and Meier 1958). The Kaplan-Meier survival curve is a function of the data only, and in the absence of censored values it follows the proportion of individuals alive at each time interval during the holding phase of the experiment and seeks a point in time when survival stabilizes. Plots were made on six selected species for the three live VLs, showing their 95% confidence intervals. Analyses were conducted with the “survival” package in R 3.4.3 (R Core Team 2017).

Table 3. Vitality levels (VL) and survival index of discarded invertebrates estimated on deck in a) Catalan coast; b) Ligurian and northern Tyrrhenian Seas.

		Species	VL 1	VL 2	VL 3	VL 4	Total alive	Total assessed	Survival index
A, Catalan coast									
Continental shelf	Crinoid bed	*Antedon mediterranea*	19	2	8	0	29	29	100
		Leptometra phalangium	17	37	86	12	140	152	92.11
		Astropecten aranciacus	0	2	4	0	6	6	100
		Echinus melo	4	5	7	5	16	21	76.19
		Cidaris sp.	2	3	7	0	12	12	100
		Spinolambrus macrochelos	3	0	1	0	4	4	100
		Echinaster sepositus	9	3	4	0	16	16	100
	Muddy	*Anseropoda placenta*	0	0	6	0	6	6	100
		Astropecten irregularis	1	1	0	0	2	2	100
		Diazona violacea	4	0	0	0	4	4	100
		Liocarcinus depurator	1	0	1	1	2	3	66.67
		Microcosmus sulcatus	2	0	0	0	2	2	100
		Ophiura texturata	0	0	38	0	38	38	100
		Macropipus tuberculatus	4	0	2	0	6	6	100
Slope	Muddy	*Dardanus arrososor*	5	7	0	0	12	12	100
		Goneplax rhomboides	2	0	0	0	2	2	100
		Monodaeus couchii	1	0	1	0	2	2	100
		Munida intermedia	0	0	4	2	4	6	66.67
		Nephrops norvegicus	72	143	222	354	437	791	55.25
		Total	147	204	387	375	738	1113	66.3
B, Ligurian and northern Tyrrhenian seas									
Continental shelf		*Astropecten aranciacus*	0	0	3	0	3	3	100
		Galeodea spp.	0	84	0	0	84	84	100
		Goneplax rhomboides	7	0	0	236	7	243	2.88
		Macropodia spp.	45	60	0	0	105	105	100
		Medorippe lanata	21	20	6	955	47	1002	4.69
		Ophiura spp.	0	3	0	0	3	3	100
		Parapenaeu slongirostris	10	4	10	519	24	543	4.42
		Processa spp.	0	0	2	0	2	2	100
		Solenocera membranacea	88	134	187	8923	409	9332	4.38
		Squilla mantis	45	103	114	1863	262	2125	12.33
Slope		*Dardanus arrosor*	4	10	0	28	14	42	33.33
		Pagurus spp.	17	17	6	0	40	40	100
		Astropecten irregularis	0	2	2	8	4	12	33.33
		Macropipus tuberculatus	22	31	32	187	85	272	31.25
		Munida intermedia	2	0	4	13	6	19	31.58
		Nephrops norvegicus	2	5	25	173	32	205	15.61
		Pagurus excavatus	5	16	18	452	39	491	7.94
		Paromola cuvieri	0	0	2	0	2	2	100
		Total	268	489	410	13357	1167	14524	46.41

Table 4. Percentages of the four vitality levels in each study area for the two species of invertebrates subjected to MCRS.

	***N. norvegicus* (CC)**	***N. norvegicus* (LTS)**	***P. longirostris* (LTS)**
Excellent (1)	9.10	0.98	1.84
Good (2)	18.08	2.44	0.74
Poor (3)	28.07	12.20	1.84
Dying or dead (4)	44.75	84.39	95.58

3. Results

3.1 Survival on deck

The VLs of discarded invertebrates were identified for each individual of each selected species. Table 3 shows the results of each VL analysed in each study area, according to the continental shelf and slope and the corresponding habitat. From the discarded fraction, the species presented in Table 3 were scored with vitality levels in both study areas. Among the invertebrates captured, only *N. norvegicus* and *P. longirostris* were subject to minimum conservation reference sizes (MCRS) (Council Reg. EC 1967/2006), while the rest of the discarded invertebrates were non-regulated species.

A survival index of 100% was shown by 14 species in the Catalan coast area and 6 in the Ligurian and northern Tyrrhenian seas area, and *Astropecten aranciacus* and the genus *Ophiura* were common in both areas. The species *Munida intermedia, Goneplax rhomboids* and *Macropipus tuberculatus* showed a lower survival index in the Ligurian and northern Tyrrhenian seas area, where the processed number of individual was higher and the results were probably more reliable. On the other hand, *N. norvegicus* gave more robust results in the Catalan coast area, where more individuals were analysed.

The percentages of the four vitality levels (VL) of Norway lobster and deep water rose shrimp, the two commercial species subjected to MCRS, are presented in Table 4 for both areas. Values of each VL represent the percentage of the total number of individuals for each level from the total analysed hauls. The Catalan coast area showed the highest percentages of live VLs.

The Wilcoxon test was carried out only with the variables Haul Time and Depth. The results showed no significance between depth and survival. However, the test found significant differences in survival due to Haul time with a p-value $<2.2e-16$ and $W=7898500$. The mean duration of hauls with live animals was 217.39 min, while the mean duration with dead animals was 236.12 min (i.e. a 9% time increase).

3.2 Survival at the laboratory

The survival estimation at the laboratory was carried out only for the specimens collected in the Catalan coast study area. The analyses were undertaken only with the invertebrate species with a higher number of individuals scored with VL on deck previous to the discard (Table 3A); a total of six species were analysed. Of the six invertebrates analysed, the three in Figure 2 showed 100% survival for 96 h in the aquarium experiment.

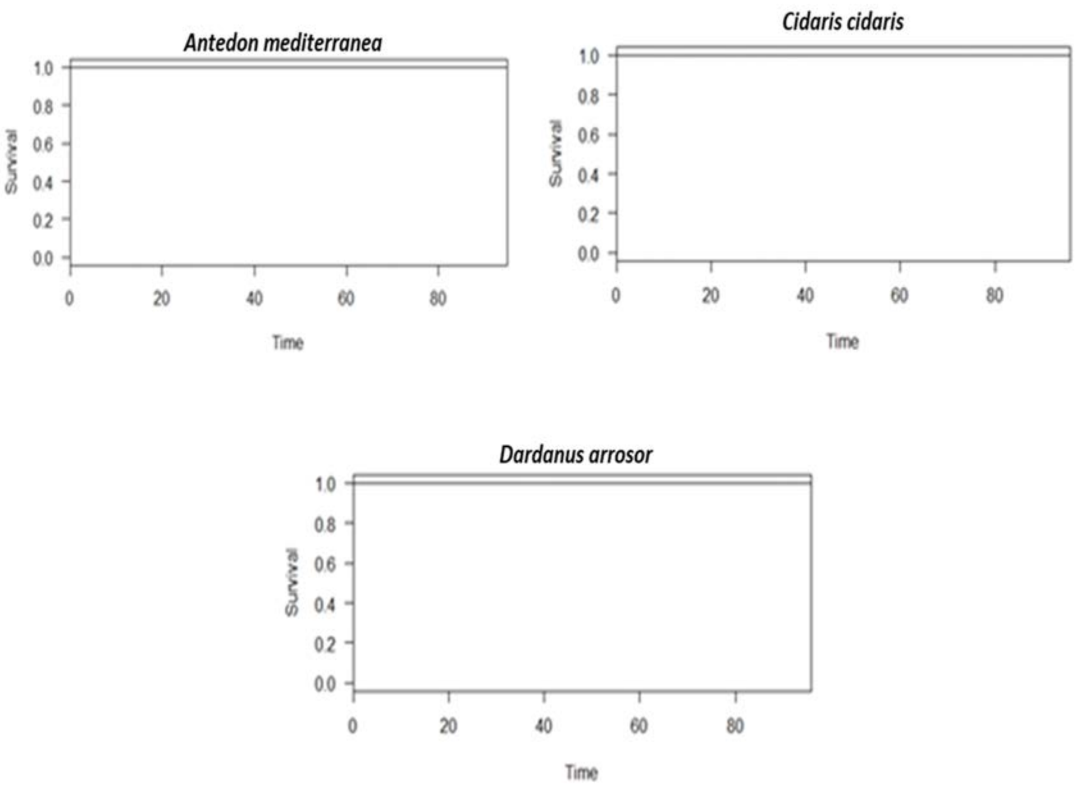

Fig. 2. - Analysis with the K-M model to assess the survival of *Antedon mediterranea, Cidaris cidaris* and *Dardanus arrosor*.

The species *Leptometra phalangium* showed more than 90% survival, and only after 30 h did the percentage of mortality increase (Fig. 3; Table 5A, B) in the specimens with the VL 3. VLs 1 and 2 showed no evidence of mortality, but VL 3 showed an evident no stability of survival.

Similar results were shown for the species *Ophiura texturata*. In this case the first evidence of mortality appeared after 66 h in VL 3, but the percentage of survival was still high (>79 %). VLs 1 and 2 showed no evidence of mortality (Fig. 4, Table 5C, D). The last species studied in the aquarium was *Echinaster sepositum*, which showed mortality at 6 h of the experiment in VL 3, but maintained a steady survival rate >90% until the end of the experiment (Fig. 5 and Table 5).

Table 5. Results of K-M model to analyse the survival of *Leptometra phalangium* (A and B), *Ophiura texturata* (C and D), *Echinaster sepositus* (E); n.risk, live animals; n.event, dead animals.

time	n.risk	n.event	survival	std.err	lower 95% CI	upper 95% CI
A. Longitudinal survival over 96 hours and three levels of vitality						
0	152	12	0.921	0.0219	0.879	0.965
30	140	4	0.895	0.0249	0.847	0.945
42	136	4	0.868	0.0274	0.816	0.924
54	132	9	0.809	0.0319	0.749	0.874
66	123	4	0.783	0.0334	0.720	0.851
78	119	4	0.757	0.0348	0.691	0.828
90	115	5	0.724	0.0363	0.656	0.798
B. Mortality events at the laboratory at vitality levels 2 and 3 at T0 (0.0H.=3)						
30	86	4	0.953	0.0227	0.910	0.999
42	82	4	0.907	0.0313	0.848	0.970
54	78	9	0.802	0.0429	0.722	0.891
66	69	4	0.756	0.0463	0.670	0.852
78	65	4	0.709	0.0490	0.620	0.812
90	61	5	0.651	0.0514	0.558	0.760
C. Longitudinal survival over 96 hours at the three vitality levels						
66	38	4	0.895	0.0498	0.802	0.998
78	34	2	0.842	0.0592	0.734	0.966
90	32	2	0.789	0.0661	0.670	0.930
D. Mortality events at the laboratory at vitality level 3 at T3 (T3.28.5H.=3)						
66	36	4	0.889	0.0524	0.792	0.998
78	32	2	0.833	0.0621	0.720	0.964
90	30	2	0.778	0.0693	0.653	0.926
E. Longitudinal survival over 96 hours at the three vitality levels						
6	16	1	0.938	0.0605	0.826	1

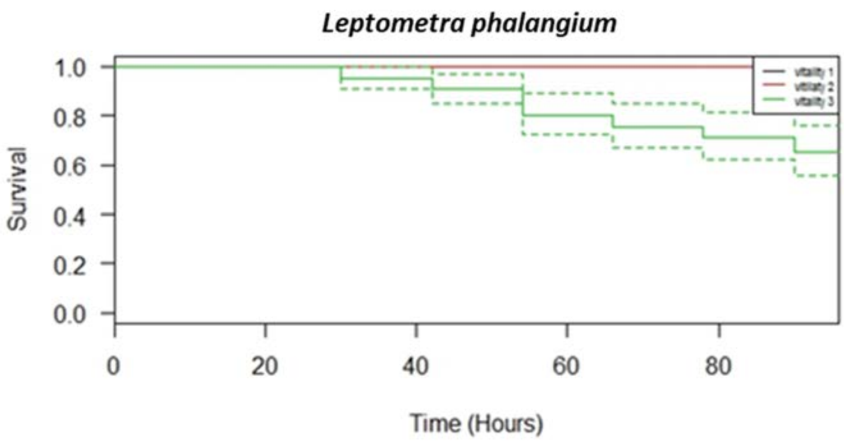

Fig. 3. – K-M model to assess the survival of *Leptometra phalangium* at vitality levels 1, 2 and 3.

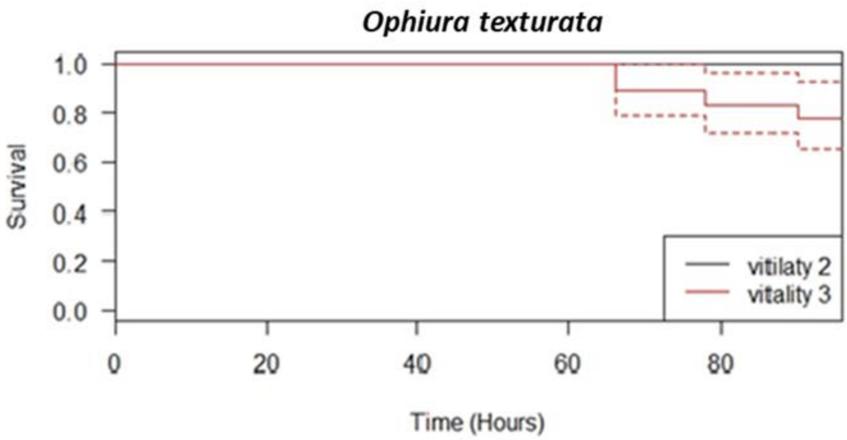

Fig. 4. – K-M model to assess the survival of *Ophuira texturata* at vitality levels 2 and 3.

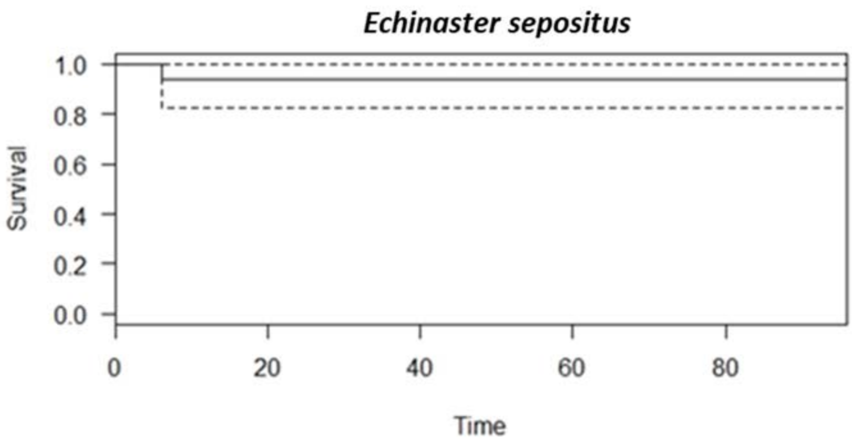

Fig. 5. – K-M model to assess the survival of *Echinaster sepositum* at vitality level 3.

4. Discussion

This study was carried out with those individuals that showed signs of vitality when arriving on board, which means they were still alive. In fact, there was a low number of specimens that could be assessed, and this may indicate the severe impact of trawling on the seabed and benthic communities (Kaiser and Spencer 1995; Jennings et al., 2001). The preservation of exploited resources is probably the main goal of fishery management, but the perturbation of chronic fishing activity on fishing grounds has negative ecological effects leading to high levels of mortality (DFO 2006, Van Denderen et al., 2013).

Several studies have evidenced an improvement in the health of exploited resources when effort limitation and seasonal or temporal closures of trawl fishing activities are implemented (Demestre et al., 2008; Demestre et al., 2015; Pipitone et al., 2000), but the effects at the level of benthic communities remain less well known. The by-catch of invertebrates in bottom trawling yields a high amount of epifauna or infauna that have important functions for the sea floor ecology. For instance, echinoderms or gastropods are important bioturbators and comprise several feeding guilds, such as deposit or filter feeders, or predators (e.g. *Echinus melo, Spatangus purpureus, Echinaster sepositus, Ophiura texturata, Chlamys opercularis, Calliostoma granulatum* and *Aporrhais serresianus*). These organisms play an important role in ecosystem function by maintaining or enhancing secondary marine production. They are very sensitive to disturbance and easily destroyed by fishing impact, and their decrease could have lasting consequences for benthos-pelagic processes (Lohrer et al., 2004; Demestre et al., 2017; de Juan et al., 2011), because the good status of the habitats in which the fisheries resources live depends to a large extent on these organisms.

In order to maintain the good status of the sea bottom, one of the priority actions to be taken is to determine the mortality levels of routinely discarded species. A study carried out near the Catalan coast area related the effects of trawl fishing and feeding of the red mullet *Mullus barbatus* (Muntadas et al., 2015), showing negative effects due to changes in benthic functional components in the fishing ground. In areas where there was no fishing (fishing closure areas) the macroinfauna which constitutes the food base for *M. barbatus* was significantly more abundant than in areas disturbed by the trawl. Changes in the habitat structure (homogenization) and functionality of benthic communities caused by fishing can alter the normal supply of food (e.g. polychaetes and crustaceans) for both adult and juvenile red mullet (Fiorentino et al., 2008; Muntadas et al., 2014). Furthermore, as a consequence of the habitat alteration, the characteristics of the seabed that serves as a nursery, spawning or growing habitat could be modified, with possible negative consequences on future recruitment of the species.

The rates of survival shown by invertebrates in both areas investigated in this study showed great variability between VLs of the same species once the individuals had been captured and deposited on the deck of the trawler. Mortality levels also vary from one species to another, depending mainly on the biological and functional traits of each species, such as fragility, emergent or surface position, filter feeding and sedentary motility (Costello et al., 2015; Muntadas et al., 2015). External protection is one of the most relevant traits for increasing survival, as evidenced by the monitoring of VLs on deck to analyse immediate mortality. In both areas the majority of crustaceans remained alive, even reaching percentages of 100%. Invertebrates with regeneration traits such as echinoderms also have a high level of survival.

We went one step further in estimating discarded invertebrate mortality by attempting to identify and separate the injuries of each individual on deck according to its VL. Individuals with VL 1 and 2 at time T0 (time of release on deck) survived on deck until they were released into the sea in a maximum time of 30 min, but those with VL 3 showed low survival on deck. The experiments at the laboratory to analyse survival at 96 h confirmed this behaviour for all analysed species. At the laboratory it was evident that when the survival was not 100% it was because the organism was at VL 3 when released on deck, and in fewer cases at VL 2.

The results of the Wilcoxon test indicated that Haul Time was an important factor for improving organisms' survival on deck. Injuries increased and VL decreased when invertebrates arrive on deck after long hauls, as was observed in the continental shell hauls, which showed a higher survival of species of crinoids and crustaceans (Table 4 and Figs 3-5). Consequently, failure of individuals to survive for a long time in the laboratory experiment is due to their low VL when they were left on deck. It is therefore important to handle the organisms on deck quickly and safely to increase their survival when they are discarded back into the sea. During fishing operations on deck, it is recommendable to keep the organisms under a wet cover to avoid drying. Another easy method for improving the survival of discards could be a direct operating system such as a duct with water from the deck for throwing animals back into the sea.

It must be taken into account that, in addition to the unhealthy state of the invertebrates who died during the experiment, the mortality may also have been due to the captivity conditions, where no food was available and the environment was only similar to the most appropriate habitat. However, the possibility of discarded invertebrates escaping predators or obtaining food is low because of the injuries they suffer during capture (Ramsay et al., 1996; Bergmann and Moore 2001; IngólfssonIng et al., 2007). Therefore, our experimental results can be assumed as a proxy to the level of survival of discards at sea.

According to the Common Fisheries Policy and the landing obligation to prevent discarding of regulated species (MCRS, Council Reg. EC 1967/2006, Art. 15.4b), a high level of post-capture survival can be adduced by member states to include an exemption from the landing obligation in their discard management plans. Our results for the survival of *N. norvegicus* can be considered a starting point with information focused on the aim of a possible species exemption but, obviously, more studies based on larger samplings need to be carried out before this exemption can be recommended. Conversely, a second crustacean species regulated by MCRS, *Parapenaeus longirostris*, showed low survival and would not be a good candidate for exemption.

The species selected for survival estimations were the most representative of different taxonomic levels and were of ecological importance in their habitats. In view of this, the 100% survival of the crinoids *A. mediterranea* and even *L. phalangium*, whose increase in post-release mortality started at VL 3, shows that the impact of trawling on crinoid beds may be less serious than assumed until now, as most crinoid individuals would survive the encounter with trawlers and postcatch release. Furthermore, in many cases crinoid beds are essential habitats for nursery and spawning areas of some commercial species (Colloca et al., 2004). The other two echinoderms that were assessed, *O. texturata* and *E. sepositum*, gave similar results, both starting mortality at VL 3. Therefore, the results may suggest again an optimistic possibility for maintaining a good environment status and a sustainable structure on the soft-sediment habitats that form the majority of trawl fishing grounds (Piet and Hintzen 2012). However, to maintain this optimistic perspective and a good environment status on the Mediterranean fishing grounds, it is mandatory to contain the current exploitation levels, especially in other types of habitat that may be even more sensitive to trawling than crinoid beds, such as maerl and Isidella (Kamenos et al., 2004; Mastrototaro et al., 2017). To achieve this, fishing activity and fishing effort must be reduced, temporal and spatial closures and even permanent closed areas must be implemented, and the measures regulating the reduction of discards must be implemented (FAO 2011).

The results of the present work offer some new knowledge on the survival of discarded invertebrates that may be useful for improving ecosystem health and productivity. Nevertheless, it should be regarded as a starting point, because mortality after discards at sea depends on many factors, such as susceptibility to predation and lower competitiveness for obtaining food (Bergmann and Moore 2001; Demestre et al., 2000; Kaiser et al., 2006). Knowing levels of survival of discarded invertebrates helps to obtain a more realistic image of the state of the benthic ecosystem, and consequently of the fishing grounds. The sustainability of the exploited populations depends on the conservation of these habitats, because a large part of their life cycle takes place in them.

Acknowledgements

This study received funding from the European Commission's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 634495 for the project "Science, Technology, and Society Initiative to Minimize Unwanted Catches in European Fisheries" (MINOUW). The authors wish to thank José Guzman, Vicens Rovira, Joan Pou, Josep Maria Viñas, Maurizio Bistazzoni and Armando Costaglione, captains of the fishing vessels Milagros I, Mariner, Punta Santa Anna, Estelada, Angela Madre and Real, respectively, and all their crews, for their support in the sampling at sea. We also thank Elvira Martínez for helping on survival experiments at laboratory ZAE from the ICM.

Capítulo 2b

Seasonal variation in the survival of discarded *Nephrops norvegicus* in a NW Mediterranean bottom-trawl fishery

Seasonal variation in the survival of discarded *Nephrops norvegicus* in a NW Mediterranean bottom-trawl fishery

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Publicado: Fisheries research 230, October 2020, 105671.

https://doi.org/10.1016/j.fishres.2020.105671

Abstract: The landing obligation in the revised European Union Common Fisheries Policy allows for exemptions to obligatory landing of the entire catch for species for which “high survival” of discards can be demonstrated. *Nephrops* norvegicus is an important target species in many fisheries across Europe in the Mediterranean Sea, NE Atlantic Ocean and North Sea. Historically, Mediterranean fisheries have had a high discard rate of small-sized *Nephrops*, and it is suspected that this unwanted component of the catch may have a high survival potential that is comparable to those of other EU fisheries, where survival rates of up to 0.56 have been demonstrated. However, to date, no investigations have confirmed a high discard survival rate for *Nephrops* in the Mediterranean Sea. Furthermore, the environmental, technical and biological characteristics that could affect *Nephrops* survival have been shown to be substantially different from those in the survival assessments conducted in the NE Atlantic and the North Sea. To address this knowledge gap, this study was conducted to determine the survival of *Nephrops* discarded from trawls in the Mediterranean Sea. The survival and vitality status of the discarded *Nephrops* removed from trawl catches were monitored onboard and for 14 days in the laboratory. The results showed seasonality in survival, with the highest survival rate in winter (0.74; CI: 0.7−0.78), lower survival in spring (0.36; CI: 0.31−0.41) and the lowest survival in summer (0.06; CI: 0.04−0.09). Survival was monitored to the asymptote in all cases, and season and vitality status were shown to have statistically significant relationships with survival.

Keywords: Survival, Discards, *Nephrops norvegicus,* Vitality assessment, Landing obligation

1. Introduction

Norway lobster (*Nephrops norvegicus*) is a commercially important species that is widely distributed throughout Europe fisheries from the Mediterranean Sea and the NE Atlantic to the northern North Sea and Baltic Sea (Vasilakopoulos and Maravelias 2016). The total discard rates in the trawl fishery targeting Mediterranean *Nephrops* can reach 30 % of the total catch, comprising a high proportion of undersized (i.e., below the minimum conservation reference size (MCRS) specimens of *Nephrops* (García -de-Vinuesa et al., 2018).

The introduction of the landing obligation (LO) in the European Union's (EU) Common Fisheries Policy aims to shift harvesting patterns in EU fisheries by reducing unwanted catches by banning discarding practices and encouraging more selective capture methods (EU Reg., 1380/, 2013). Currently, the LO applies to regulated species, that is, species for which there is a quota or MCRS; it stipulates that no unwanted catches of regulated species can be discarded: they must be landed in port and not used for human consumption ((EC) No 850/ 1998). However, there are situations (exemptions) in which animals may be legitimately released (discarded) from commercial fishing catches, such as those with high survival – when the survival of a species from a particular fishery has been demonstrated to be sufficiently high to justify its release (Art. 15 of EU Reg., 1380/, 2013). For the high survival exemption to be implemented, fishery-specific evidence must be presented to the European Commission, which will consider the merits of an exemption to the LO on a case-by-case basis (Rihan et al., 2019).

Technical measures have been in place for decades in an attempt to avoid catching undersized animals in the Mediterranean *Nephrops* fisheries, including an MCRS of 20 mm in carapace length (CL) and minimum trawl cod-end mesh sizes of 40 mm (square-mesh) or 50 mm (diamond) (Council Regulation (EC) No., 1967/, 2006; GFCM/29/ 2005/1). However, these control measures have not been not fully effective because substantial numbers of undersized *Nephrops* between 15 and 20 mm CL continue to be caught and discarded, contravening the LO that has been in place since 1st January 2019 (García -de-Vinuesa et al., 2018). Furthermore, the size of maturity for *Nephrops* in the Mediterranean Sea is between 30 and 36 mm in CL (Relini et al., 1998), which is much larger than the MCRS. As such, immature individuals between 20 and 30 cm are routinely caught legally, which makes this management strategy questionable.

Several studies carried out in Atlantic coastal waters have demonstrated that *Nephrops* is likely to have a high discard survival rate (Mehault et al., 2016; Mérillet et al., 2018). In 2016, we carried out preliminary tests to evaluate whether *Nephrops* or *Parapenaeus longirostris* were good candidates for a study that could demonstrate a high discard survival rate in Mediterranean crustacean fisheries. It was concluded that only *Nephrops* was a good candidate, and these results were published by Demestre et al. (2018). However, these tests were limited to vitality assessment on deck, and it became evident that a more robust methodology and larger sampling efforts were needed to eventually demonstrate a high discard survival rate for *Nephrops*. To date, no investigations have confirmed a high discard survival rate for *Nephrops* in the Mediterranean Sea despite its commercial importance and the repeated realization that technical regulatory measures have proven ineffective in reducing unwanted catch.

Several factors are thought to potentially affect the survival of discarded *Nephrops*, including technical, biological and environmental characteristics (Giomi et al., 2008; ICES-WKMEDS, 2014; Mehault et al., 2016). Specifically, *Nephrops* survival varied seasonally in assessments conducted in the Atlantic (Castro et al., 2003; Albalat et al., 2010), and this may be related to biological factors such as the period of maturation and reproduction (Relini et al., 1998). Survival may also be affected by handling practices on deck (Bergmann et al., 2001; Macbeth et al., 2006) and the duration of air exposure (Davis and Olla 2002; Broadhurst et al., 2006; Benoît et al., 2010, 2012). Rapid and abrupt changes in salinity and temperature have also been shown to negatively affect the survival of *Nephrops* (Harris and Ulmenstrand 2004) and other crustaceans (Giomi et al., 2008).

One of the main differences between the Atlantic and Mediterranean *Nephrops* fisheries is the depth of the fishing grounds. In the North Sea and in areas close to the Iberian Peninsula, such as the northern Bay of Biscay, *Nephrops* are fished from 50 to 80 m (Ungfors et al., 2013), whereas in the western Mediterranean Sea, *Nephrops* populations are mainly located in deep water on the continental slope from 300 to 600 m (Maynou and Sardà 1997; Maynou et al., 1998; Abello et al., 2002). This depth difference has important implications for several aspects related to the survival of discarded *Nephrops* catches. At a technical level, deep water fishing in the Mediterranean generally entails a single 6−7 hour haul per day, compared to areas near Scotland where 2 hauls of 3 or 4 h are generally carried out (Johnson et al., 2013). Therefore, captured individuals are likely under stress for longer periods. The fishing depths also create a large temperature differential between the nearly constant 13 °C year-round bottom temperature in the Mediterranean deep sea (Hopkins 1985) and the warm to hot air temperatures to which catches are exposed once hauled on deck. In summer, air temperatures higher than 30 °C are common, and surface water temperatures can be 26 °C or higher in July and August (Spanish National Meteorological Office, AEMET). Sudden seasonal changes in temperature may affect the survival of discarded animals differently in the Mediterranean and Atlantic since the temperature difference to which *Nephrops* catches are exposed in the Atlantic is generally lower.

Three methods for assessing the survival of discarded animals have been described by the ICES Workshop on Methods for Estimating Discard Survival (WKMEDS): captive observation, vitality assessments (i.e., indicators of survival potential) and tagging/biotelemetry (ICES 2014). In isolation, each method has limitations that can restrict the usefulness of the produced survival estimates. However, when two or more of these methods are combined, there is clear potential for considerable synergistic benefits, including reduced resource requirements and improved accuracy and precision of survival estimates. (ICES 2014; ICES CRR 2020).

The study presented here aimed to assess the survival of discarded *Nephrops* from a Mediterranean trawl fishery on the Catalan Coast, NE Spain. It used captive observations and vitality assessments to determine the seasonal variability in survival rates as well as likely causes of mortality. The results may be used to improve the sustainable management of this fishery by better informing decisions about the most appropriate measures for promoting the survival of released *Nephrops*.

2. Material and methods

2.1 Study area and fishing Characteristics

The animals included in this study were sampled from 10 hauls, which were carried out in three seasonal blocks between 2016 and 2017 (spring from 24 May to 14 June; summer from 6 to 20 September; winter from 21 December to 12 February) on the “Malica” fishing grounds, which are adjacent to Blanes on the Catalan coast (Fig. 1). Malica was chosen as the study area because it has characteristics typical of Mediterranean *Nephrops* fishing grounds with regard to both the commercial importance and discard rates of *Nephrops* (García-de-Vinuesa et al., 2018). The sampling was done onboard a commercial trawler (20.6 m length, 600 HP and 64.91 GT). The cod-end nominal mesh was 50 mm diamond. The towing speed of the trawl was between 2.3 and 2.8 knots. The tow durations of the hauls were between 127 and 376 min (Table 1), with a maximum fishing depth of 408 m. The catch weight was measured through data extrapolation of subsamples taken on board and varied, by haul, between 44.1 and 248.8 kg. The air temperature was measured onboard and ranged between 5 °C in winter and 25 °C in summer. The surface water temperature was captured from official data published by the L'Estartit weather station (operated by the Catalonia Meteorological Service) near the study area and ranged between 13 °C in winter and 24 °C in summer. The temperature of the black plastic non-slip surface where the catch was sorted was between 30 and 37 °C when measured in the summer of 2019. Additionally, more cloud cover was observed in summer than in spring and winter.

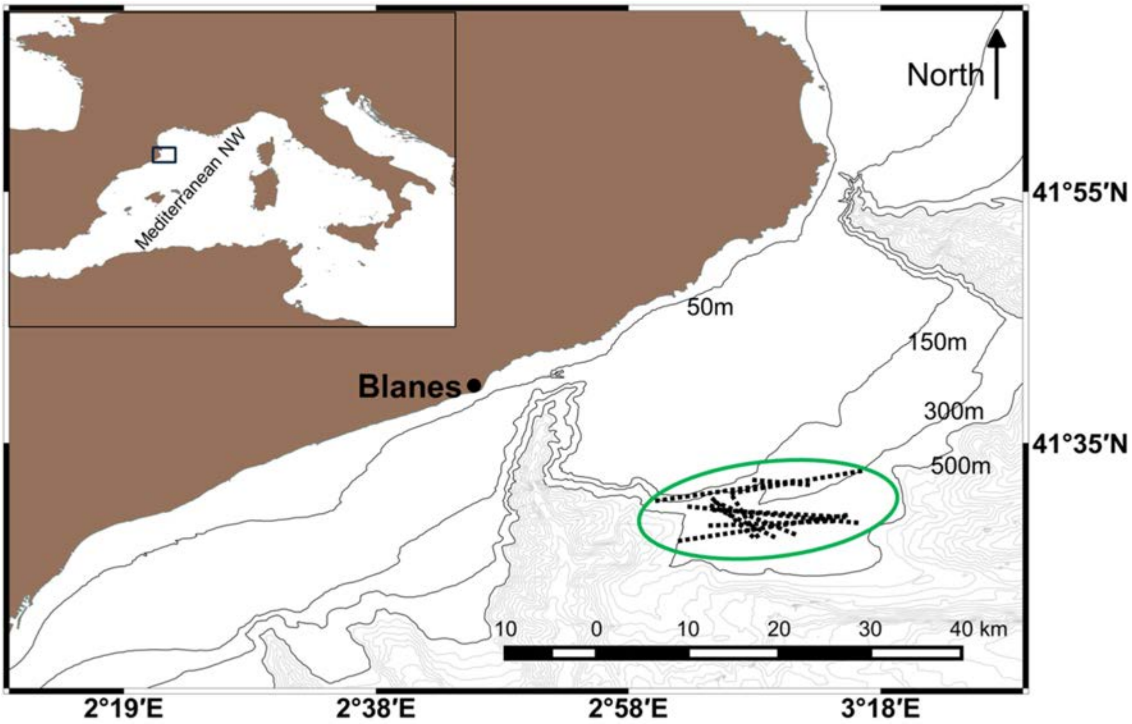


Fig. 1.- Catalan Coast study area and haul locations: the "Malica" fishing grounds are shown by a green ellipse adjacent to the port of Blanes, and the 10 selected hauls for the study are indicated by dashed black lines.

Table 1: Characteristics of each haul used for the captivity experiment: Rep ID indicates the experiment replicas in chronological order taking into account the seasons (Spr (spring), Sum (summer), Win (winter)), sample size (n), cloudiness from 1 (no clouds) to 8 (totally cloudy) (Cld (1-8)), air temperature (AT), surface water temperature (WT), haul depth (Dph), haul duration (HT) and catch weight (CW).

Rep ID	n	Cld (1-8)	AT (°C)	WT (°C)	Dph (m)	HT (min)	C.W (kg)
Spr1	141	1	20	16	311	350	248.8
Spr2	87	1	18	20	362	210	158.5
Spr3	111	2	23	21	364	132	106
Sum1	112	3	22	23	320	376	100.9
Sum2	100	7	25	23	307	127	44.1
Sum3	101	8	23	24	320	188	86.9
Win1	109	1	7	14	275	180	91.5
Win2	108	1	12	13	309	120	112.55
Win3	115	2	7	15	408	315	180
Win4	116	1	5	15	247	345	118.7

2.2. Vitality assessment

The vitality status of each sampled *Nephrops* was assessed using the categorical vitality assessment (CVA) method (ICES CRR, 2020) and to avoid stressing the specimens, the evaluations were carried out as quickly as possible. This assessment method used both behavioural indicators and the presence of injuries to determine the vitality status of each animal with respect to one of four categories: 1 (excellent), 2 (good), 3 (poor) or 4 (dying or dead) (Table 2). In the event of a contradiction between the behaviour and injuries, the most negative assessment prevailed.

Table 2. Criteria for the Categorical Vitality Assessment (CVA) for *Nephrops norvegicus* in a western Mediterranean trawl fishery.

Vitality status	Code	Behavioural	Injuries
Excellent	1	Spasmodic body movements, aggressive posture	No external injury
Good	2	Continuous body movements, responds to contact	Superficial injury or loss of some pereiopods
Poor	3	Weak body movements, can move antennas, pereiopods or maxillipeds	Loss of some chelipeds or cuts
Dying or dead	4	No movement, does not respond to repeated contact	Deep cuts, crushed or punctured carapace

2.3. Sampling and survival experiment

To determine the seasonal variation in survival, a total of 10 replicate treatment hauls were carried out: 4 replicates in winter, 3 in spring and 3 in summer. A total of 1100 discarded *Nephrops* (< 27 mm CL) were sampled from the catch and were briefly held aboard the fishing vessel before transfer to a shore-based aquarium for monitoring, including a 2−3 hour transit time to port. During the 2-week monitoring period, a total of 13 CVAs were carried out (T0…T12), either onboard the vessel, following transit or during captivity in the landbased aquaria (Table 3). Individuals classified in the excellent vitality category (Table 2) at time T0 were taken as pseudo-controls for each haul, as per WKMEDS guidelines (ICES CRR, 2020).

Table 3. Location and timing of vitality status assessments from the beginning of the experiment (T0=0.5 hours) to the end (T12= 2 weeks).

Places/vitality assesment in time	T0 0.5H	T1 4H	T2 16H	T3 28H	T4 40H	T5 52H	T6 64H	T7 76H	T8 88H	T9 94H	T10 1 W	T11 1.5 W	T12 2 W
On-board	x												
Transfer		x											
Aquaria (ICM)			x	x	x	x	x	x	x	x	x	x	X

2.3.1. On-board

After hauling in the net, the catch was deposited onboard on a nonslip black plastic surface, which followed the standard catch handling and sorting process of the vessel's crew. Immediately after this, *Nephrops* specimens that had been separated from the comercial fraction and were to be discarded were randomly sampled and transferred into one rectangular plastic holding tank containing surface sea water, which was renewed intermittently (Fig. 2). No more than 30 min after the catch was brought onboard, the initial CVA (T0) was conducted, and the animals were segregated according to their vitality status (Table 2) into one of four separate white plastic containers (50 L each). The initial sample size was limited to ∼100 individuals to avoid overcrowding the specimens in any one of the four holding containers (for a maximum of 40 animals per container). The white plastic containers were supplied with running surface sea water and 5 Dajana oxygen-producing tablets per hour to prevent hypoxia. In addition, to controlling the water temperature in the containers during the warmer seasons (spring and summer), the containers were placed on ice packs during transit to the port and then transported to the laboratory in an air-conditioned vehicle (18 °C). It took a maximum of four hours to transfer the specimens back to the shore-based aquaria (i.e., a maximum of 3 h transit to the port, and 1 h from the port to the laboratory).

Fig. 2.- *Nephrops norvegicus* in the catch (left) and white plastic containers filled with surface seawater into which the samples were transferred (right).

2.3.2. Transfer

The specimens, which were transported in the white plastic containers, were transferred as quickly as possible to the experimental aquarium facilities at the Institute of Marine Science (ICM) in Barcelona. The first hours of the assessment were the most critical period for survival, so to achieve better outcomes, an additional vitality assessment was performed when the animals were transferred into the aquaria (T1). At this moment, the CL of the largest individuals was measured to assess the maximum size of the discards. Here, individuals were again segregated into separate sections in the aquarium tanks according to their vitality status, and animals in state 4 (dead or moribund) were removed.

2.3.3. In the aquarium (ICM laboratory)

This phase was conducted in the experimental tanks at ICM. Eight further assessments (T2…T9) were conducted in the first 94 h of the observation period, with one assessment every 12 h. Later, three further assessments were made 1 week, 1.5 weeks and 2 weeks after the start of the experiment (T10, T11 and T12).

Each aquarium was partitioned into three sections, with one for each state of vitality (i.e., 1, 2 and 3). Each section had dimensions of 80 cm in length, 45 cm in width and 25 cm in depth and a maximum of 20 specimens per section to avoid overcrowding. When there was a change in the state of vitality in a specimen, it was isolated into another reserved aquarium with the same characteristics as previously described to avoid confusing it with other specimens.

To simulate natural conditions, each aquarium had an open-circuit seawater system; a water temperature between 13 and 14 °C; a photoperiod adapted to the natural light cycle; a black canvas to dim the light; periodic controls of salinity, nitrates, nitrites and silicates; and bricks and rocks to provide artificial shelter and free movements within all sections. The specimens were not fed during the assessment as in the other works (Mehault et al., 2016; Mérillet et al., 2018) because *Nephrops* can naturally survive long periods without eating

2.4. Data analysis

The vitality at the initial time (T0) per season was explored by calculating the percentages of individuals in each vitality state.

2.4.1. Kaplan-Meier

Kaplan-Meier (KM) analysis (Kaplan and Meier 1958) was used to describe survivorship over time (with a 95 % confidence interval) for the pooled season data, pooled CVA data, replicates and pseudo-controls. To study the possible significant differences among the seasons and vitality statuses over time, a log-rank test was conducted (see below). These analyses were conducted using the “survival” and “survminer” packages in R 3.3.1 (R Development Core Team 2016).

2.4.2. Parametric survival modelling

The generalized parametric survival model proposed by Benoît et al. (2015) was fitted to each replicate experiment in each season to estimate the survival rate at the asymptote, as per WKMEDS guidelines (ICES CRR 2020). The time to reach the asymptote can also be estimated from this model to determine whether the monitoring period was sufficient to allow all treatment-related mortality to be expressed.

This approach models the survivorship of *Nephrops* over time based on the mortality and censoring times observed in the experiment. The model was written as follows:

$$S(t) = \tau \cdot \left(\pi \exp[-(\alpha t)^{\gamma}] + (1 - \pi)\right)$$

where S(t) is the survivorship at time t, α and γ are parameters of a Weibull survival distribution that describes the mortality of *Nephrops* as a result of the treatment (i.e., capture, transfer and captivity in aquaria), τ is the initial survival rate and π describes an asymptote in the discard mortality following the treatment (for a derivation, see Benoît et al., 2015). In this model, α, γ, π, and τ are all estimated parameters. From these parameters, one can separately estimate the initial capture and handling mortality rate, 1 − τ, and the post-transfer mortality rate (i.e., in captivity), τπ; thus, from these metrics, the total treatment mortality rate is 1 − +τ τπ. One can also estimate the time at which total treatment mortality has approximately reached its asymptote (i.e., within 99.9 %) as follows:

$$t_{asymptote} = \alpha^{-1} \log(1000)^{1/\gamma}$$

This variable was estimated for each replicate to confirm that all discard-related mortality had occurred by the end of the monitoring period.

The survival model was fitted to the data using maximum likelihood. The fit suitability was assessed by comparing the model predictions and non-parametric Kaplan-Meier estimates of survivorship.

2.4.3. Factors of survival

After confirming that mortality had reached an asymptote in all treatments by the end of the monitoring period (see Results), the relationship between the survival of *Nephrops*, season and vitality status (at T0) was investigated using a GLM with a binomial distribution and logit link function fitted to the overall survival data (i.e., after 14 days (336 h) of monitoring). To define survival after 14 days as the dependent variable, the *Nephrops* specimens with vitality 1, 2 and 3 were assigned codes of 1 (alive), while those in state 4 were assigned codes of 0 (dead). The best model was selected with a stepwise procedure based on the minimization of the Akaike information criterion (AIC), and the variance explained by the model was estimated using Nagelkerke's pseudo R2 (Nagelkerke 1991).

3. Results

3.1. Survival and vitality analysis

The mean overall survival at day 14 was 0.43 (95 % confidence interval, CI: 0.40−0.46). There was substantial variability between replicates (Table 4), with the highest survival in trial "Win4″ (Table 1) with 0.85 (CI: 0.78−0.91). The pseudo-controls (animals with vitality status: 1) typically had high survival rates between 0.67 and 1, except in the summer, which had survival rates of 0.5 or less.

Table 4. Results of the survival rates (S.rate) together with their respective pseudo-controls and 95% confidence intervals (C.I.) for each replicate.

Rep ID	S. rate	C.I.	n	Control S. rate	Control C.I.	Control n
Spr1	0.23	0.17-0.32	141	0.67	0.50-0.89	24
Spr2	0.51	0.41-0.62	87	0.91	0.79-1	21
Spr3	0.4	0.32-0.5	111	0.83	0.69-1	23
Sum1	0	-	112	0	-	4
Sum2	0.11	0.06-0.19	100	0.28	0.13-0.59	18
Sum3	0.07	0.03-0.14	101	0.5	0.23-1	6
Win1	0.73	0.65-0.81	109	0.91	0.81-1	32
Win2	0.69	0.6-0.78	108	0.85	0.74-0.98	34
Win3	0.7	0.62-0.79	115	0.94	0.87-1	36
Win4	0.85	0.78-0.91	116	1	-	35

The mean survival at day 14 showed significant seasonal variation: that in winter was 0.74 (CI: 0.67−0.78); in spring, 0.36 (CI: 0.31−0.41); and in summer, 0.06 (CI: 0.04−0.09) (Fig. 3). There were also significant differences in mean survival over time between vitality statuses (at T0), with the highest survival for *Nephrops* that were initially in excellent (1) condition, followed by those in good (2) and poor (3) conditions and ultimately those that were dying or dead (4) (Fig. 4). The highest mean survival (at day 14) was for those that were initially in the excellent (1) state, with 0.81 (CI: 0.76−0.86), while the lowest survival was observed in dead and dying *Nephrops* (vitality status 4), with 0.07 (CI: 0.04−0.11).

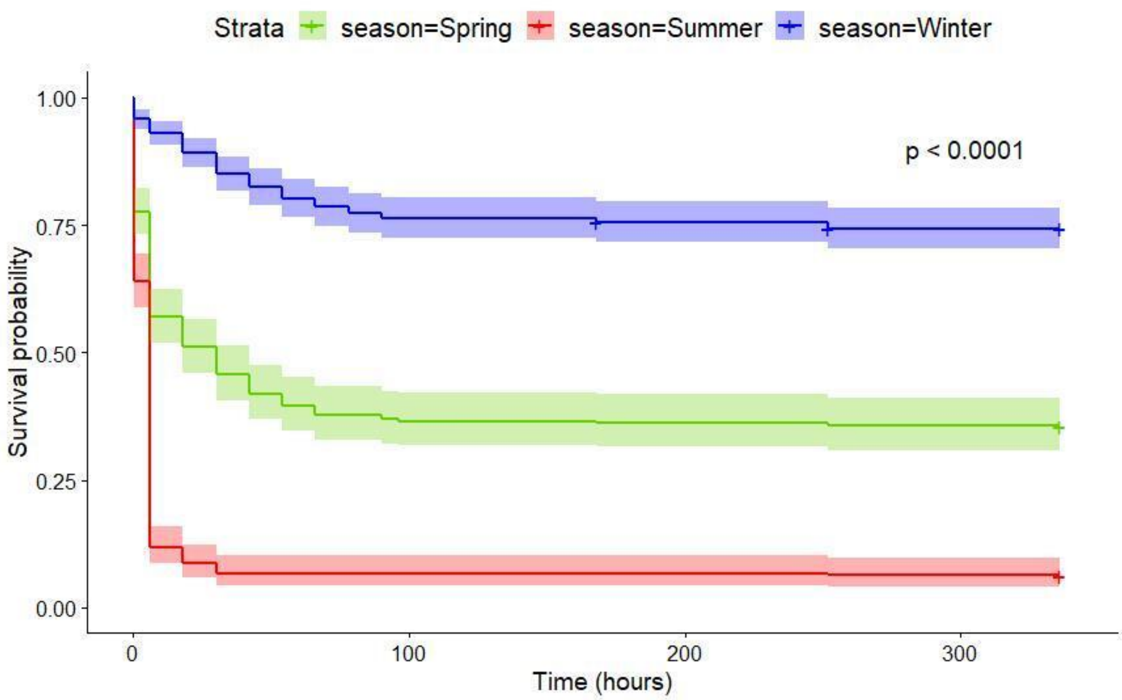


Fig. 3.- Kaplan-Meier survival curves (with 95% confidence intervals) for *Nephrops norvegicus* caught in demersal trawls in different seasons: spring (green), summer (red) and winter (blue); data from different trials/replicates were pooled within seasons.

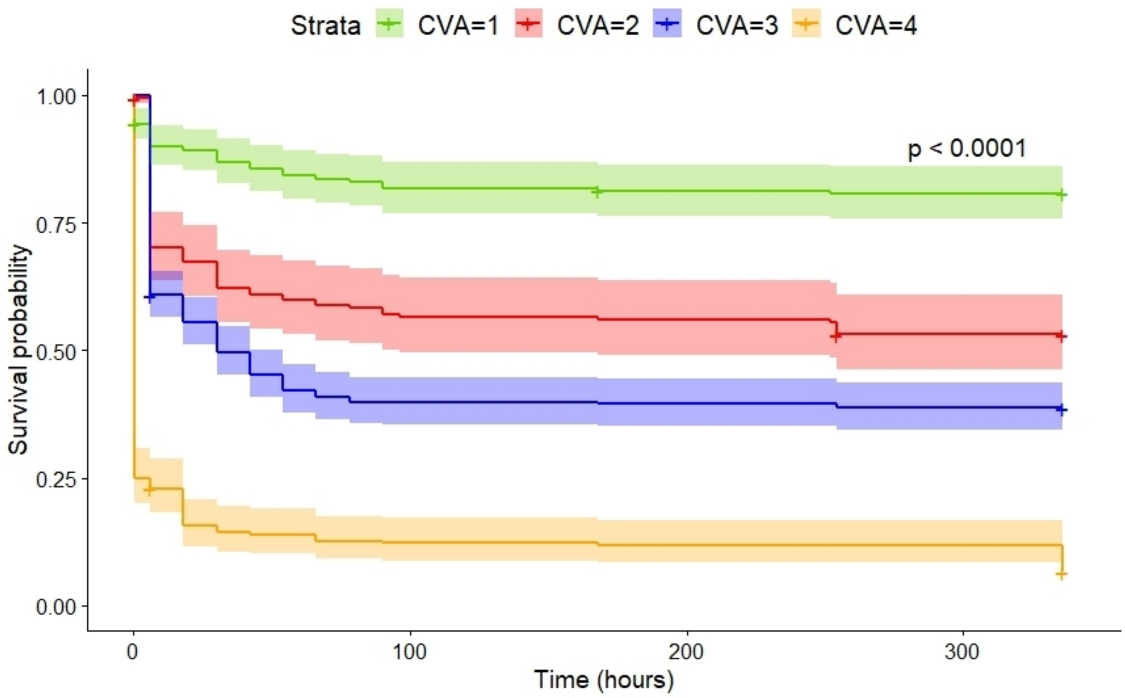


Fig. 4.- Kaplan-Meier survival curves (with 95% confidence intervals) for *Nephrops norvegicus* with respect to vitality (CVA category at t_0): excellent (1) (green), good (2) (red), poor (3) (blue) and dead or dying (4) (yellow); data were pooled across replicates/trials and seasons.

The results of the vitality status analysis at T0 by season showed higher percentages of animals in excellent and good conditions in winter, which decreased in spring and was the lowest in summer (Table 5). In addition, the percentage of dead or dying individuals at the initial time (T0) was lower during winter and increased in spring until reaching the highest percentage in summer.

Table 5: Percentage of *Nephrops* individuals at each state of vitality per season at the beginning of the experiment (T0).

Season/CVA	1 (% excellent)	2 (% good)	3 (% poor)	4 (% dying or dead)
Spring	20.6	17.3	36.9	25.3
Summer	9.2	11.4	41.8	37.6
Winter	30.6	19.4	42.9	7.2

3.2. Parametric survival modelling

The predicted survivorship functions from the parametric survival model followed the Kaplan-Meier estimates very well (Fig. 5). Estimates of tasymptote from the model were within the range of those during the monitoring periods for all experimental trials (Table 6).

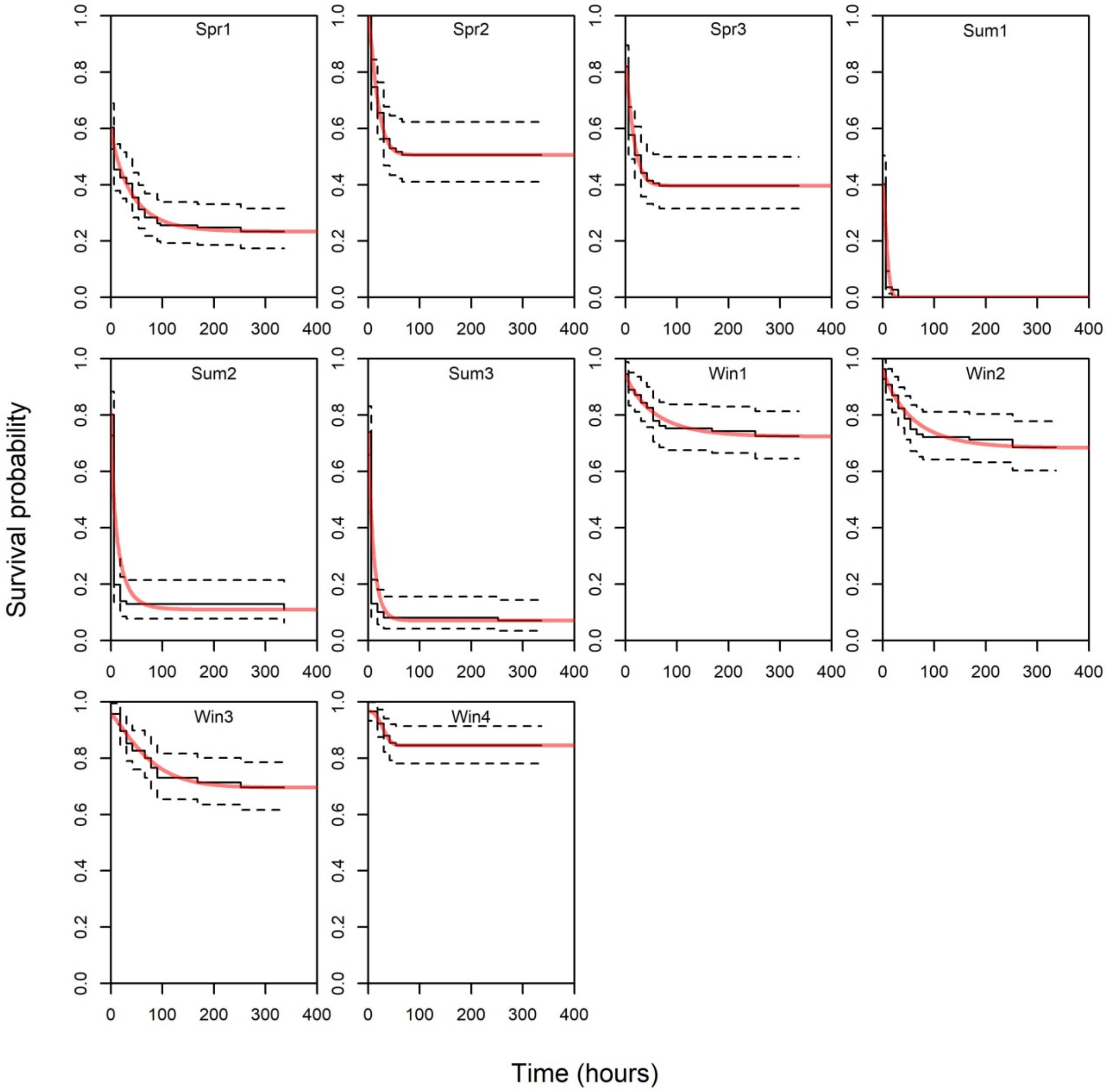


Fig. 5.- Survivorship functions for *Nephrops norvegicus* sorted chronologically from left to right from spring to winter in the 10 experimental trials based on non-parametric Kaplan-Meier estimates (solid line; 95% confidence interval, dashed line) and predictions from the parametric survival model (red line).

Table 6. Estimates of $t_{asymptote}$ from the parametric model for each replica (Rep ID).

Season	Rep ID	$t_{asymptote}$
Spring	SPR1	227.4
	SPR2	64.1
	SPR3	60.9
Summer	SUM1	23.8
	SUM2	93.5
	SUM3	54.3
Winter	WIN1	307.1
	WIN2	314.0
	WIN3	261.6
	WIN4	58.4

The estimated initial mortality (0 h, 1 − τ) was the highest and most variable for the spring and summer experimental trials, ranging from 0.18 to 0.60, except for trial "Spr2", which had no initial mortality (Fig. 6). In contrast, the estimated initial mortality was substantially lower in the winter, ranging between 0.04 and 0.06.

The estimated total discard mortality (at day 14) based on the parametric model was very similar to the Kaplan-Meier survival results (Table 4). The greatest mortality was in the summer experiment and ranged from 0.9 to 1.0 (Fig. 6). The uncertainty for the estimate for trial "Sum1" was elevated because all individuals died, resulting in uncertainty in the survival asymptote parameter π. Estimates for π for spring were somewhat lower, ranging from 0.49 to 0.77, while estimates for winter were by far the lowest, ranging from 0.16 to 0.32. The confidence intervals for those estimates did not overlap those for the trials in other seasons.

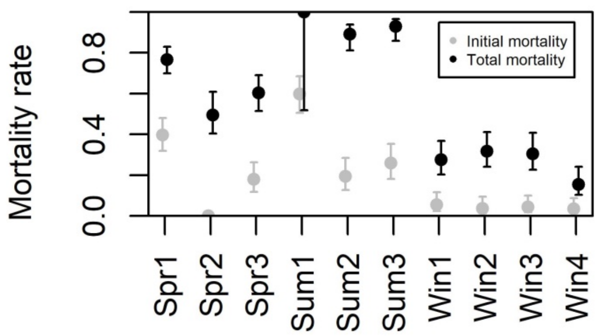


Fig. 6.- Estimates (with 95% confidence intervals) of the initial (grey) and total (black) mortality for each trial. Each trial is numbered sequentially within each season: spring (Spr), summer (Sum) and winter (Win).

3.3. Factors of survival

The deviance explained in the GLM model of survival (at day 14) was 39.79 %. Survival differed significantly between seasons, as did the vitality status (Table 7). The parameter estimates (Table 7) confirmed that survival was higher in winter and lower in summer in comparison to in spring (baseline). Moreover, the survival for vitality statuses 2, 3 and 4 was consecutively lower than that for state 1 (baseline). A significant interaction between season and vitality resulted from the survival patterns for *Nephrops* with vitality status 3 in winter.

Table 7. GLM model of survival at day 14 (336 hours), with significance Pr (> | z |) where significant values are shown in bold font and standard error (Std.error), the value of the Z statistic and the estimate are shown for each parameter. The proportions of deviance explained by the increasingly more complex models were: 27.13% (season only, AIC:1100.1), 39.16% (season and vitality status, AIC: 935.58), 39.79% (season and vitality status with interaction AIC: 928.01).

Time (14 days)	Estimate	Std.error	Z value	Pr(>|z|)
Intercept	1.35	0.30	4.50	**6.76E-06**
Factor(Season)Summer	-2.65	0.55	-4.82	**1.43E-06**
Factor(Season)Winter	1.09	0.43	2.51	**0.01**
factor(vitality)2	-1.61	0.40	-3.97	**7.68E-05**
factor(vitality)3	-2.02	0.36	-5.65	**1.65E-08**
factor(vitality)4	-4.81	0.66	-7.30	**2.97E-13**
Factor(Season)Summer:factor(vitality)2	1.05	0.78	1.35	0.18
Factor(Season)Winter:factor(vitality)2	0.31	0.57	0.55	0.58
Factor(Season)Summer:factor(vitality)3	0.30	0.72	0.41	0.68
Factor(Season)Winter:factor(vitality)3	0.23	0.50	0.45	0.65
Factor(Season)Summer:factor(vitality)4	1.33	1.29	1.04	0.30
Factor(Season)Winter:factor(vitality)4	1.99	0.81	2.44	**0.01**

4. Discussion

This study has for the first time provided empirical evidence for the survival of discarded *Nephrops* removed from the catch of a commercial trawl in the Mediterranean Sea. The overall mean survival of 0.43 (CI: 0.40−0.46) was comparable to the mean survival rates of ~0.5 observed for *Nephrops* sampled from trawl catches in the Atlantic at comparable latitudes (e.g., Mehault et al., 2016; Mérillet et al., 2018). All of these survival assessments, including that in the present study, used similar methods to determine post-capture and handling mortality, namely, captive observation (ICES CRR 2020).

Captive observation assesses the effects of a treatment by monitoring specimens in a suitable holding facility for a sufficient period for any resultant mortality to be expressed. Containment facilities and conditions can influence the survival of marine animals in captive observation studies (ICES WKMEDS

2014). In previous studies, separate boxes and/or cells have been used to house individual *Nephrops* due to their cannibalistic behaviour (Sarda and Valladares 1990). While this avoids cannibalism, it can restrict freedom of movement, which could negatively impact welfare and therefore survival. Our approach provided freedom of movement and places to hide, which better replicated conditions experienced by *Nephrops* when they are returned to their natural habitat.

To demonstrate that captivity itself has not contributed to the observed mortality, it is recommended that suitable captivity control be employed (ICES CRR 2020). In other survival assessments of *Nephrops* (e.g., Campos et al., 2015; Mérillet et al., 2018), control animals were captured using traps or short duration trawl hauls to try to obtain *Nephrops* in excellent condition. However, traps tend to select larger *Nephrops* that are not representative of discards from the trawl fishery (García -de-Vinuesa et al., 2018), while short trawl haul control groups can have survival rates that are only marginally higher than those of the treatment groups (Mérillet et al., 2018). In our study, we selected individuals identified by the CVA as having vitality status 1 (excellent) as the pseudo-controls (as suggested by ICES CRR 2020). This provided us with a subset of *Nephrops* with an appropriate size range and no notable injuries. This method works on the premise that if the pseudo-control survival is close to 1.0, then the handling and captivity that the animals are subjected to after sampling has not been detrimental to them and so is less likely to have affected the mortality observed in other specimens (ICES CRR 2020). Conversely, if the pseudo-control survival is substantially less than 1.0, this does not conclusively infer that there was a captivity effect, but it does reduce our confidence that the observed survival in the treatments was not biased (underestimated) (ICES CRR 2020). In general, the pseudo-control survival was high, with a mean value of 0.81 (CI: 0.76−0.86). However, summer was an exception, with pseudo-control survival of between 0 and 0.5. In addition, during the summer, the number of control animals was the lowest in the study, which could lead to less precise estimation of its survival. As already demonstrated in other studies (e.g., Giomi et al., 2008), we theorized that the temperature changes between the normal, stable habitat of *Nephrops* on the seabed (∼13 °C) and the higher temperatures at the water surface (∼24 °C), in the air (∼25 °C) and on the catch-sorting mat (30−37 °C) induced thermal shock, which led to high mortality during the first hours of experimentation (T0-T1) on animals that previously seemed to be in an excellent state of vitality.

Refrigeration during the transfer of individuals may also not have been sufficient to achieve an appropriate water temperature (∼13 °C), and future studies should employ water cooling systems during the transfer, as has already been tested in another *Nephrops* survival study (Mérillet et al., 2018). Water temperatures above 13 °C during transfer could have resulted in the underestimation of survival rates during warmer periods. However, this possible underestimation does not contradict the seasonal effects on *Nephrops* survival because the CVA carried out at the beginning of the experiment (T0) was not subject to this potential experimental bias. Moreover, the initial mortality (at T0) showed marked seasonality, with higher mortality in summer (0.26−0.6) than in winter (0.05−0.1) and high percentages of animals in excellent and good condition in winter, which decreased in spring and were the lowest in summer.

Seasonal variation in *Nephrops* survival has also been observed in the Atlantic (Castro et al., 2003; Lund et al., 2009; Mérillet et al., 2018), although those specimens showed greater survival during the summer. In our study, the air temperature reached 25 °C. This temperature was higher than those in other studies carried out in the Atlantic Ocean, where the temperature in summer was approximately 19.4 °C (Mérillet et al., 2018). In addition, in the Mediterranean during late spring and summer (i.e., between May and September) large *Nephrops* moult prior to reproduction (Sarda and Valladares 1990) and ovary maturation and brooding occurs in female *Nephrops* (Relini et al., 1998). This could make them more vulnerable to injury during trawling, and the reduced metabolic capacity may reduce the animal's ability to cope with the stresses of capture and handling. Thus, it would be inappropriate to discard *Nephrops* during this period because it will result in low survival. The potential for sex-biased survival should be further investigated in *Nephrops* and other crustaceans.

Another challenge faced by all captive observation survival assessments was ensuring that the monitoring period had sufficient resolution and was long enough to observe all treatment-related mortality. In this study, most mortality was observed during the first 72 h post-treatment, while we monitored mortality every 12 h up to 96 h and then at a coarser interval until 14 days. Furthermore, the survival functions in all replicates were shown to have reached asymptote within the 14-day (336 h) monitoring period.

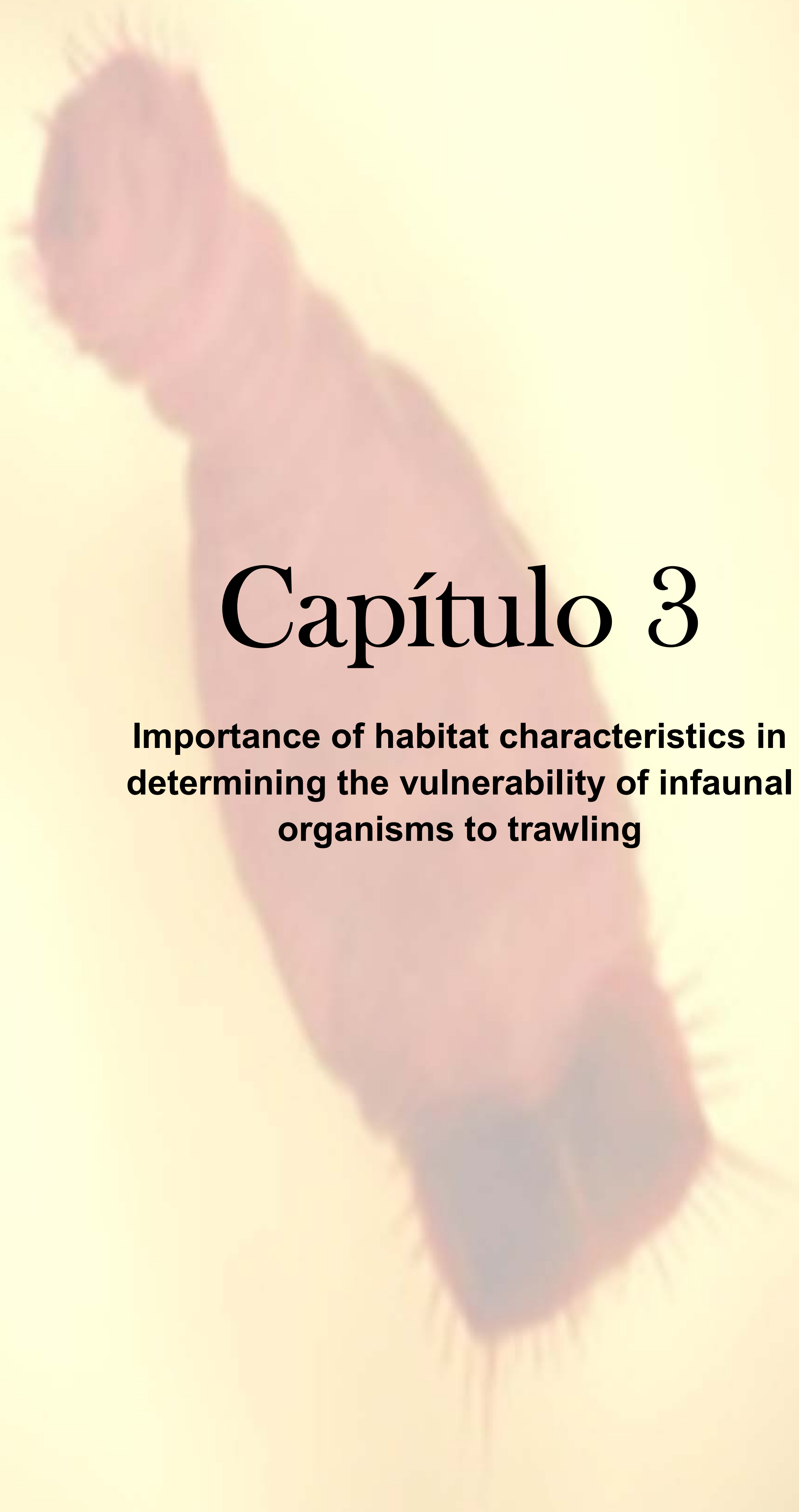
This study provided a systematic definition of vitality status for *Nephrops*, which is the ICES recommendation for survival assessments (ICES 2014). The GLM analysis showed a significant relationship between vitality status and survival. In addition, a log-rank test showed consistent significant differences in survival over time between all vitality levels, where the highest survival was for the excellent state (1) and the lowest was for the dead or moribund state (4). This agreed with similar studies carried out in the Atlantic (Armstrong et al., 2016; Mérillet et al., 2018) and suggested that vitality may be a useful mortality predictor for discarded *Nephrops* in the Mediterranean. However, there were some inconsistencies noted between the behavioural and injury criteria used to define the *Nephrops* vitality status. Moreover, the fact that the latter group, "dead or moribund" (vitality status 4), did not consistently have zero survival indicated that the criteria used to define this vitality status could benefit from some refinement. Future work should more thoroughly investigate the relationship between initial vitality status and survival of *Nephrops* with the aim of improving our mortality predictor for discarded *Nephrops* in the Mediterranean.

5. Conclusion

The seasonal variation in post-release mortality, which had very high values in summer, suggests that a survival exemption to allow post-release discarding in summer would be ineffective. Only seasonal fishery closure during the summer months would be appropriate to avoid producing fishing mortality on undersized *Nephrops*. Alternatively, technical improvements should be made onboard fishing boats to promote the survival of unwanted catches, such as protection from direct sunlight, refrigerated holding tanks, and white (or refrigerated) non-slip sorting tables.

Acknowledgments

This work was funded by the research project MINOUW (H2020- SFS-2014-2) of the European Commission (contract n° 634495). We also want to thank the crew of the "Mariner" trawler for the help during sampling, which was indispensable for the achievement of the objectives of this work, and the Association of Fishermen of Blanes.



Capítulo 3

Importance of habitat characteristics in determining the vulnerability of infaunal organisms to trawling

Importance of habitat characteristics in determining the vulnerability of infaunal organisms to trawling

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Bajo revisión: Aquatic Conservation: Marine and Freshwater Ecosystems

Abstract

1 Trawling reduces the abundance and diversity of infaunal communities, which have an essential ecological role in highly vulnerable and productive Mediterranean benthic habitats, such as maerl beds, and thus negatively affects habitat functionality by decreasing the food supply available to demersal fish stocks.

2 Infaunal communities are specifically adapted to each type of marine habitat, so their responses to trawling may also differ among habitats and should be assessed on an individual basis.

3 In this study, a biological trait approach (BTA) was used to evaluate the responses of infauna to trawling effects by analysing the differences in vulnerability between the infaunal communities of maerl beds and muddy bottoms. The applied BTA considered the infaunal biological characteristics related to trawl impact, which was used to define six ranks of vulnerability.

4 The results showed significant differences in vulnerability to trawling between the infaunal communities of maerl and muddy habitats. So was evidenced a lower abundance of highly vulnerable infauna in the trawled maerl beds than in the untrawled ones. In the muddy habitats, differences in the abundances of very-high, medium-low and low vulnerability infauna were found between the trawled and untrawled fishing grounds.

5 Regarding the vulnerability differences between the maerl and muddy infaunal communities and taking into account other important attributes of each habitat, such as fishing effort or physical and biological characteristics, we proposed

specific management measures aimed at sustainable exploitation to promote recovery of the infaunal communities by suggesting a paradigm shift in the classic concept of exploitation and conservation.

Keywords: maerl, biological trait approach, infauna, vulnerability, trawling, muddy, benthic.

1. Introduction

Trawling has a heavy physical impact on benthic habitats, as it reduces the abundance and diversity of benthic communities (Thrush et al., 1998; Kaiser et al., 2000; Thrush and Dayton 2002). One of the most strongly affected communities is infauna (Sanchez et al., 2000; Koch et al., 2009; Muntadas et al., 2016), which show important, specific adaptations for each type of marine habitat and facilitate important functions by regulating the processes of nutrient flow through the water column and acting as a food source for species of high commercial value (Lohrer et al., 2004; Lloret et al., 2007; de Juan and Hewitt 2014; Muntadas et al., 2015).

Maerl beds are considered one of the habitats with the greatest diversity and abundance of benthic species, including infaunal communities, in the Mediterranean Sea (Gimenez-Casalduero et al., 2001; Ballesteros 2006; Ramos-Espla and Luque 2008; Sheehan et al., 2015). These habitats are structured by red algae, which create to calcareous formations called rodoliths that shape a type of three-dimensional structure that accommodates infaunal species specifically adapted to hard substrates (Rose and Pleijel 2001; Sciberras et al., 2009). These unique habitats benefit commercial fish species, such as red mullet (*Mullus spp*) and common pandora (*Pagellus erythrinus*), which carry out various vital habitat functions, such as reproduction, growth and feeding; as a result, maerl beds can be considered essential fish habitats (EFHs) (García-de-Vinuesa et al., 2018; Auster and Langton 1998). In addition, due to the slow growth of red algae, maerl beds are considered a non-renewable resource. For these reasons, maerl beds are included in annex I of the Habitats Directive as a priority habitat for conservation (EU Directive 92/43/EEC). Furthermore, two of the algae species that form the maerl, *Lithothamnium corallioides* and *Phymatolithon calcareum*, appear in Annex V of the directive. Although trawling on maerl habitats is currently banned by the European Union (EU Council Regulation 1967/2006), these habitats are still exploited by trawlers (Basso et al., 2017; García-de-Vinuesa et al., 2018), and the response of the associated infaunal communities to trawling has rarely been studied (Bordehore et al., 2003; Sheehan et al., 2015).

Due to their wide distribution and homogeneity, muddy bottoms have been exploited for centuries by trawling, so the response of their communities to this impact has been extensively studied (Thrush and Dayton., 2002; Demestre et al., 2008; García-de-Vinuesa et al., 2018). These habitats cannot be considered as vulnerable as maerl beds because they are poorly structured and do not have the same great abundance and diversity of benthic communities as maerl beds (Demestre et al., 2017a,b). Nevertheless, their soft substrates still shelter specifically adapted infaunal species (Del-Pilar-Ruso et al., 2009) that provide fundamental ecosystem services by serving as food for commercial species such as hake (*Merluccius merluccius*) or monkfish (*Lophius spp.*). Since both maerl beds and muddy bottoms have a specific infaunal composition, their response to trawling impacts and therefore their vulnerability may be different, so these habitat types must be evaluated individually.

Vulnerability has been defined as the susceptibility of an individual, species, population, community, or habitat to impacts from natural or anthropogenic factors (Halpern et al., 2007). From studies carried out in different habitats in different oceans and seas, it is possible to draw general conclusions regarding species vulnerability to trawling activity; in this way, it was discovered that species that show more sensitive biological traits (BTs) to the impact of trawling tend to decrease in abundance or even disappear from trawled habitats, while others whose BTs are more trawl-resistant tend to thrive in these exploited bottoms (Drabsch et al., 2001; Blanchard et al., 2004; Tiano et al., 2020). According to this principle, biological features, such as the position that a species occupies in the substrate or its mobility, fragility, external protection and feeding type, are fundamental for projecting the potential impacts of trawling on a specific animals (Kaiser & Spenser 1996; Wassenberg et al., 2002; Bozzano and Sarda 2002; de Juan et al., 2007). From the compilation of several of these BTs, it is possible to build a biological trait approach (BTA), which is a tool based on the fact that regardless of taxonomic affinity, species that share similar biological characteristics have similar responses to external stressors (Usseglio-Polatera et al., 2000; Bremner et al., 2003). Recent studies have used BTA to assess the impacts of multiple anthropogenic stressors on marine communities (e.g., Mouillot et al., 2013; de Juan et al., 2020) and specifically on the infaunal communities of muddy bottoms (Bremner 2008; Muntadas et al., 2014, 2016). However, this approach has never been used to study the vulnerability of the infauna living in maerl beds to trawling or to compare their vulnerability between different habitats. The novelty of this study is that it provides the first assessment of the vulnerability of infaunal communities to trawling in highly productive maerl beds compared to in muddy bottoms, which are some of the most disturbed marine habitats, to contribute to improving fishery management based on the essential and unique characteristics of each habitat.

2. Material and methods

2.1 Study area.

The study was carried out on the northwestern Mediterranean continental shelf (Figure 1). We studied two habitats (maerl and mud) distributed among four fishing grounds located in two study areas, Blanes and Roses. In Roses, the habitats we sampled were on two fishing grounds: one had a maerl bed located between 21 and 35 m in depth, and the other had a muddy bottom located between 26 and 40 m in depth. These two fishing grounds were not affected by trawling but had endured fishing activity from trammel nets. In Blanes, the muddy bottom study habitats were located on a fishing ground at between 70 and 113 m in depth, and the maerl beds were located at another fishing ground at between 54 and 107 m in depth. The Blanes fishing grounds support an important fishing effort by the Blanes trawl fleet (García-de-Vinuesa et al., 2018).

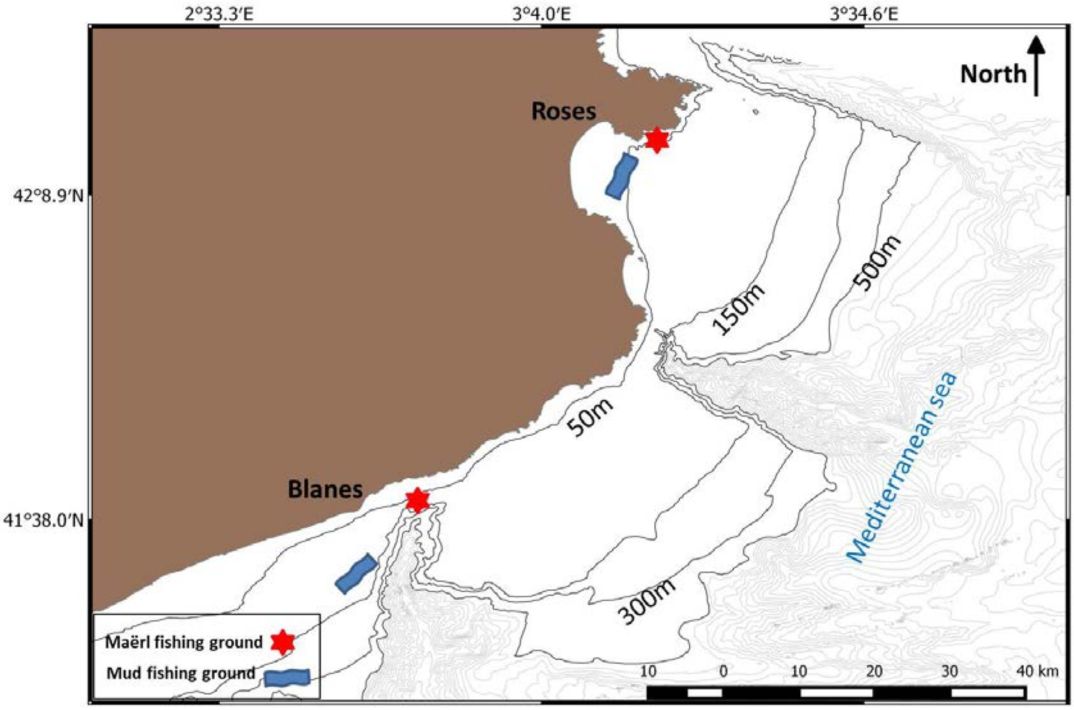

Fig 1.- Study areas: in the south, the maerl (red) and muddy (blue) fishing grounds affected by trawling in the Blanes area are indicated. In the north, the maerl (red) and muddy (blue) fishing grounds not affected by trawling in the Roses area are shown.

2.2 Sampling

To sample infauna, 0.1 m^2 Van Veen grabs were used. Three random stations were selected on each of the four fishing grounds, and five grabs were taken at each station to reach the minimum sampling size at each station (see Demestre et al., 2006 for details). The samples were filtered within the first hour after sampling through a filter with a mesh size of 1 mm and preserved in a 5% formaldehyde solution. Then, at the laboratory, the samples were cleaned of formaldehyde and stained with rose bengal until processed. Finally, the infaunal organisms were identified under a stereoscope, generally to the genera or family taxonomic level, and counted.

Two sampling periods were carried out. The first sampling period was in October 2016 during the oceanographic cruise DEEP VISION II with the R/V "García del Cid" on the two Blanes fishing grounds. The second sampling period was in October 2018; sampling was conducted on the two Roses fishing grounds from aboard a trammel net commercial fishing boat. We carried out all sampling during October to avoid possible seasonal variations in infaunal community composition (Koch et al. 2009; de Juan and Hewitt 2014).

2.3 Vulnerability ranking of infauna to trawling

A BTA was developed considering five biological traits with high sensitivity to trawling disturbance, following de Juan et al. (2007). To classify the vulnerability of taxa, each BT was split into several categories, which were assigned a code (Table 1). The motility was valued, ranging from sedentary to highly motile organisms. The environmental position was categorized as surface and subsurface, and the feeding type comprised 3 categories: filter feeders; deposit feeders; and predators, scavengers or opportunists. Fragility was classified as high, medium or low. The presence of a protective outer tube was also considered. Each category was scored for trawling sensitivity using a scale of 1 to 3 (1 = low sensitivity, 2 = moderately sensitive, 3 = highly sensitive). The assignment of categories by taxa was carried out with the information codified in the BIOTIC database maintained by the Marine Biological Association UK (http://www.marlin.ac.uk/biotic/). The biological characteristics of the included species were taken into account, which was complemented with a literature review of studies conducted in the Mediterranean and with specialist knowledge. Finally, the category scores were summarized for each taxon, which were classified into six vulnerability ranks according to their final score. These ranks were from lowest to highest vulnerability to trawling according to the vulnerability score: very low, low, medium-low, medium high, high and very high.

Table 1. List of BTs and their corresponding categories, codes and scores.

BT	Category	Code	Score
Motility	Sedentary	S	3
	Mobile	M	2
	Highly Mobile	H	1
Environmental position	Surface	S	3
	Subsurface	B	1
Feeding type	Filter feeders	F	3
	Deposit feeders	D	2
	Predators, scavengers or opportunistic	P	1
Fragility	High	H	3
	Medium	M	2
	Low	L	1
Protection (tube)	None	n	1
	Protection	p	2

2.4 Data and statistical analysis

The abundance of polychaetes, molluscs, arthropods, sipunculid, echinoderms and the remaining fauna (grouped into category "others") was standardized by individuals per square metre (individuals/m^2). Next, these groups were analysed for each maerl and muddy bottom habitat, taking into account whether they were on a fishing ground with or without trawling activity (Figures 2 and 3). To assess the similarity between the abundance of taxa (mainly at the level of family and class) in each maerl and muddy bottom habitat, a Bray-Curtis similarity index and an ANOSIM test were carried out after square root transformation of the data to reduce the influence of the dominant ranks. Then, we selected taxa from each habitat to evaluate the infaunal communities' vulnerability through the SIMPER procedure, which accounted for 85% of the dissimilarity accumulated between the trawled and untrawled fishing grounds. Within the selected taxa, a total of 22 infaunal taxa from maerl beds and 11 from muddy bottoms were included (Table 2). The Bray Curtis, ANOSIM and SIMPER analyses were carried out with the PRIMER statistical program (Clarke & Warwick 1994). The average taxon abundance was added together within each vulnerability rank, and the maerl and muddy fishing grounds were differentiated to identify possible unexpected behaviours of the vulnerability ranks (Table 3). Then, the abundance of each vulnerability rank was converted to a percentage to compare the composition of the four fishing grounds: trawled maerl, untrawled maerl, trawled mud and untrawled mud (Figure 4). Finally, a t-test was performed to identify significant differences ($p > 0.05$) in the abundances of the different vulnerability ranks between the trawled and untrawled maerl and muddy fishing grounds. A Shapiro-Wilk test was used to study normality, and Levene's test was used to study the homogeneity of the error of the variances. When normality was not observed in the data, a log-10 transformation was applied. In one case, the medium-high rank in the muddy bottoms, the data were not normally distributed. In this case, we carried out a Wilcoxon-Mann-Whitney nonparametric test to study the significant differences between the trawled and untrawled fishing grounds. All analyses were carried out using the statistical program R 3.3.1 (R Development Core Team 2016).

3. Results

3.1 Response to trawling among infauna from maerl and muddy habitats

The total abundance of the animals was greater in the maerl habitats than in the muddy habitats, and all groups of organisms had greater abundances in the maerl than in the mud, except Sipunculidae, which appeared in greatest abundance in the untrawled mud (Figures 2 and 3). The abundance (or density) of infaunal organisms in untrawled maerl was 2941 individuals/m^2, and it was similar in trawled maerl (2635 individuals/m^2). However, the abundance in trawled muddy bottoms was lower (440 individuals/m^2) than that in the untrawled muddy bottoms (975 individuals/m^2). More specific analyses in both habitats revealed important differences in abundance when comparing taxa, such as arthropods and molluscs, which presented higher abundance in untrawled fishing grounds than in trawled fishing grounds.

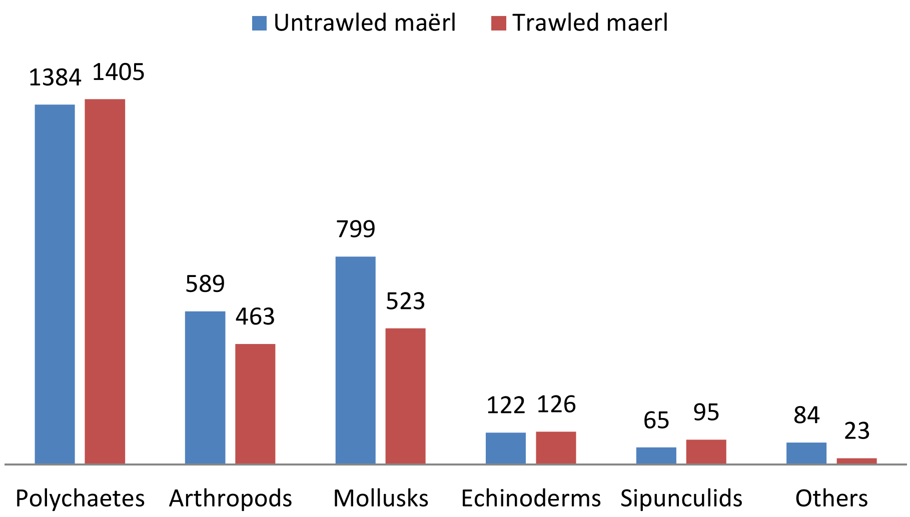

Fig 2.- Infaunal community abundance by taxon (individuals/m^2) from untrawled and trawled maerl beds

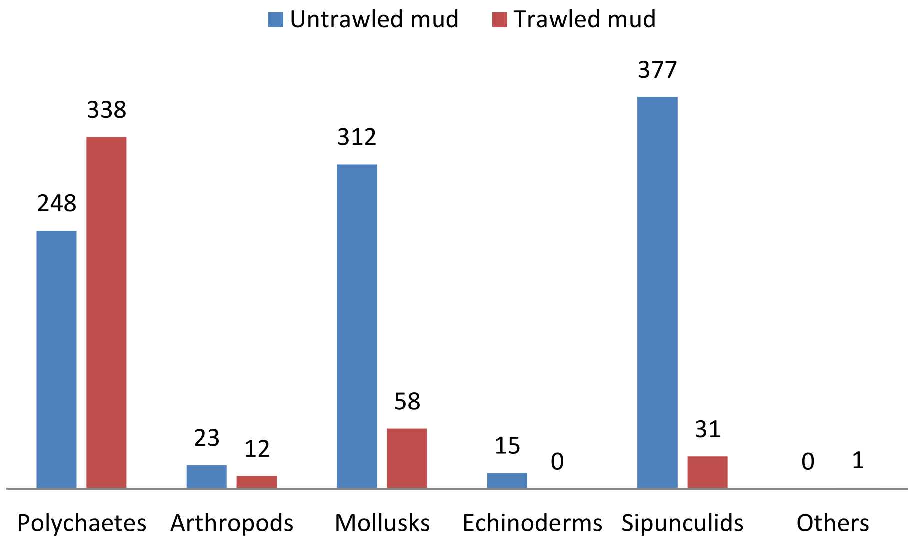

Fig 3.- Infaunal community abundance by group (individuals/m^2) from untrawled and trawled muddy bottoms

The infaunal communities from maerl and muddy fishing grounds showed 52.76% and 74.25% dissimilarity, respectively, between trawled and untrawled fishing grounds, and the ANOSIM test found that these fishing grounds differed significantly, with an R value = 0.12 (p = 0.01) for the maerl fishing grounds and an R value = 0.78 (p = 0.001) for muddy fishing grounds.

The Syllidae family was assigned the code MSPLn (Table 2), indicating that these animals were categorized mobile surface-dwelling predators or scavengers with low fragility that lacked a protective tube (Table 1). This family, together with Sipunculida, was ranked as having medium-low vulnerability, and SIMPER analysis showed that these taxa had the greatest contribution to the dissimilarity in maerl and muddy habitats, respectively. The bivalves were classified into the very high vulnerability rank with code SBFHn since they are fragile filter feeders with low mobility than live buried without protective tubes. They were the second taxon with the greatest contribution to dissimilarity in maerl habitats and the fourth greatest contribution in muddy bottom habitats. The only taxon classified as “very low” were the lumbrinerids, which were found in all fishing grounds of both habitats except on untrawled muddy habitat.

Table 2. SIMPER analysis of the infaunal communities from the maerl and muddy fishing grounds along with their vulnerability classifications: the codes indicate the categories selected from each BT by taxon (Table 1); Vul.rank indicates the different vulnerability ranks; Av ab is the average abundance for the untrawled (Un) and trawled (Tr) fishing grounds in individuals/m^2; Diss/SD is index of contribution to the dissimilarity between fishing grounds and contrib% is the percentage dissimilarity contribution.

Codes	Taxa	Vul.rank	Av. Un	Av. Tr	Diss/SD	Contrib%
Maerl fishing grounds						
MSPLn	Syllidae	Medium-low	341	732	1.23	7.5
SBFHn	Bivalvia	Very high	513	407	1.35	5.81
HSFMp	Amphipoda	Low	265	209	1.22	5.32
MSPHn	Gastropoda	High	281	114	1.1	5.13
MSPLp	Eunicidae	Low	175	118	1.11	4.67
SBDMn	Tanaidacea	Medium-high	171	54	1.46	4.42
MSPLn	Glyceridae	Medium-low	68	126	1.24	4.06
SSDLn	Magelonidae	Medium-low	106	5	0.88	4.01
SBDLn	Paraonidae	High	137	76	1.18	3.98
SSDLn	Terebellidae	High	118	55	1.46	3.83
SBDLp	Capitellidae	Low	114	88	1.16	3.81
SBDLn	Sipunculida	Medium-low	64	94	0.99	3.66
MSDMn	Echinoidea	Medium-high	76	72	1.14	3.19
HSPMn	Decapoda	Medium-low	76	74	1.25	3.13
MSPMn	Isopoda	Medium-high	41	65	1.49	3.09
MBPLn	Lumbrineridae	Very low	43	47	1.02	2.88
MSDMn	Ophiuroidea	Medium-high	34	51	1.18	2.73
SBDLp	Spionidae	Low	19	55	1.1	2.57
SSFMn	Cumacea	Very high	26	43	1.1	2.44
MSPLn	Polynoidae	Medium-low	3	34	1.12	2.02
MSPMn	Nereidae	Medium-low	38	0	0.61	2
SSDLn	Pectinariidae	High	26	7	0.74	1.83
Muddy fishing grounds						
SBDLn	Sipunculida	Medium-low	377	31	1.6	17.88
SBDLn	Paraonidae	High	88	114	1.6	10.32
SSDLp	Spionidae	Medium-high	7	65	2.08	8.93
SSFHn	Bivalvia	Very high	190	55	1.51	8.83
SBDLp	Capitellidae	Low	15	46	1.8	7.12
MSPLn	Glyceridae	Medium-low	76	7	1.07	7
MSPHn	Gastropoda	High	76	2	0.76	6.68
MBPLn	Lumbrineridae	Very low	0	30	1.77	6.09
SSOLp	Onuphidae	Medium-low	7	29	0.79	4.1
SSDLn	Terebellidae	High	26	20	0.71	3.95
SBDHn	Scaphapoda	High	45	0	0.64	3.63
SBDMn	Tanaidacea	Medium-high	11	3	0.64	2.05

3.2 Vulnerability of maerl and muddy infaunal communities to trawling

The animals with medium-low vulnerability were the most abundant in muddy and maerl habitats, followed by the very high and high vulnerability groups in the maerl fishing grounds and by high and very high vulnerability groups in the muddy fishing grounds (Table 3). As expected, in both habitats, the abundance of the most vulnerable ranks (very high, high and medium-high) was higher in untrawled fishing grounds than in trawled fishing grounds, whereas the abundances of the less vulnerable ranks (medium-low and very-low to maerl; low and very-low to mud) were higher in the trawled fishing grounds than in the untrawled fishing grounds. However, there were two unexpected outcomes: in the maerl beds, the abundance of the low vulnerability rank was slightly higher in the untrawled fishing ground than in the trawled fishing ground, whereas in the muddy habitats, the medium-low rank was higher in the untrawled fishing ground than in the trawled fishing ground.

Table 3. Average abundance (ABU) of the vulnerability ranks (Vul.rank) by untrawled (Un) or trawled (Tr) fishing grounds and habitat in individuals/m^2. Asterisks (*) indicate findings contrary to expected patterns between trawled and untrawled fishing grounds.

	Maerl fishing grounds			Muddy fishing grounds		
Vul.rank	ABU.Un.	ABU.Tr.		ABU.Un.	ABU.Tr.	
Very high	539	450		190	55	
High	562	252		235	136	
Medium-high	322	242		18	68	
Medium-low	765	1178		460	67	*
Low	573	470	*	15	46	
Very low	43	47		0	30	

The percentages of each vulnerability rank from the maerl and muddy untrawled fishing grounds were very similar; in both cases, medium-low was the rank with the highest percentage, followed by high and very high (Figure 4). However, with respect to the trawled habitats, medium-low was the rank with the highest percentage in the maerl habitat, followed by the very high and low ranks. In the muddy habitat, the rank with the highest percentage was high vulnerability, followed by the low and medium-low ranks.

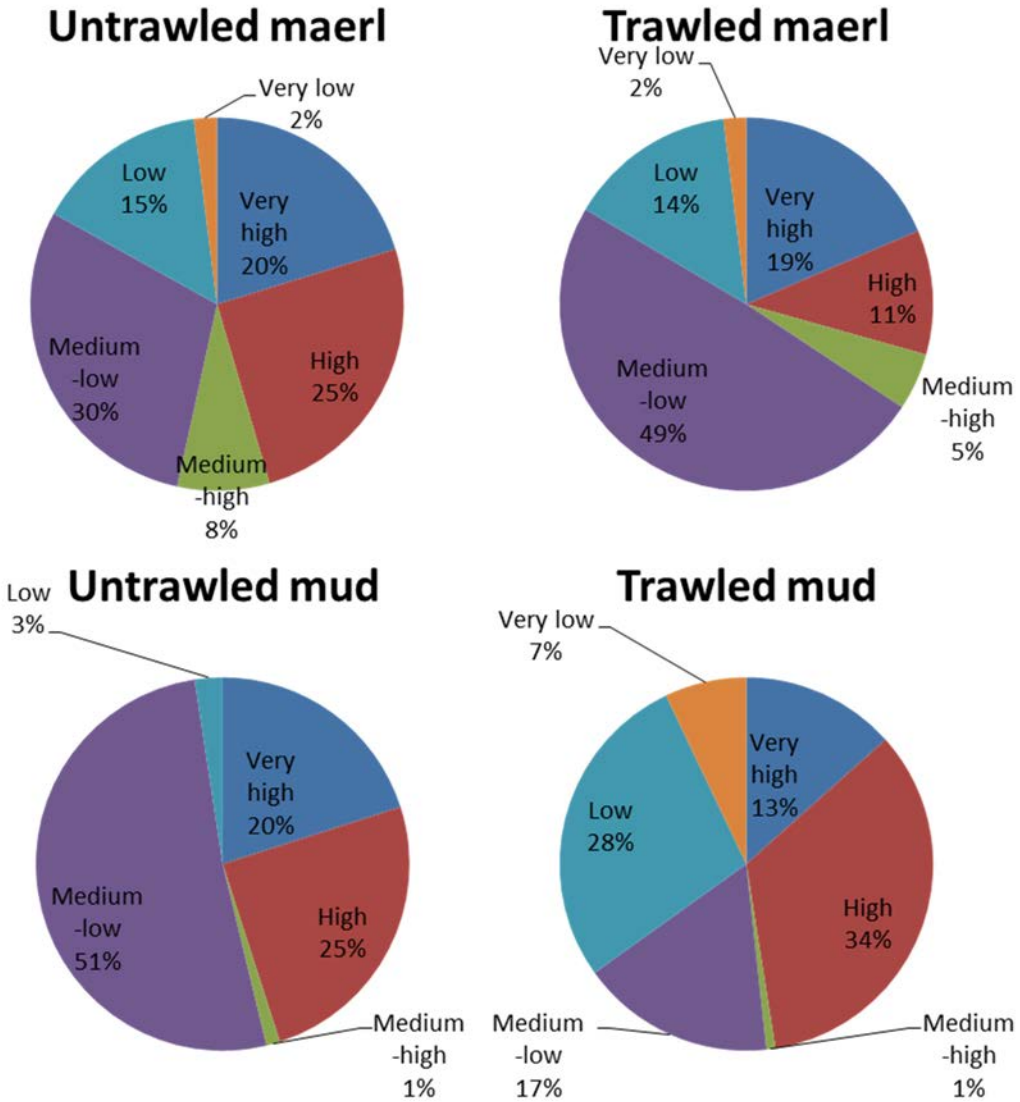

Fig 4.- Percentages of the vulnerability ranks in the abundance in untrawled and trawled maerl and muddy fishing grounds

The abundance of the high vulnerability rank was significantly higher in untrawled maerl than in trawled maerl, while there was a higher abundance of low and very low vulnerability infauna and a lower abundance of very high and medium-low vulnerability infauna in the trawled mud than in the untrawled mud. The very low rank was not tested because no animals with this classification were found in the untrawled muddy bottoms.

Table 4. Differences in the abundance of each vulnerability rank between trawled and untrawled maerl and muddy fishing grounds (T-test and Wilcoxon-Mann-Whitney test). Vulnerability indicates the different vulnerability ranks, df are the degrees of freedom, t is the t-test statistic, w is the Wilcoxon-Mann-Whitney test statistic and p-value is significance level of each test (Significance results (P<0.05) are signed in bold font).

Vul.rank	df	t	p value
Maerl fishing grounds			
Very high	25,538	-0,441	0.6629
High	22,03	-3,311	**0.0031**
Medium-high	24,867	-0,8785	0,388
Medium-low	16,47	1,1556	0.2643
Low	24,521	-1,1199	0.2736
Very low	27,899	-0,26545	0.7929
Muddy fishing grounds			
Very high	16,523	-2,8105	**0.0122**
High	18,715	-1,4002	0.1778
Medium-low	15,941	-4,4691	**0.0003**
Low	20,31	4,4762	**0.0002**
Very low	-	-	-
Medium-high		w=108	0,812

4. Discussion

The results showed for the first time the important vulnerability of infaunal maerl communities to trawling using their biological traits and evidenced differences in this vulnerability between maerl and muddy habitats. In general, the abundance of organisms belonging to each vulnerability rank responded to trawling following the expected pattern, with more vulnerable organisms being more abundant in untrawled habitats and less vulnerable organisms being more abundant in trawled habitats (de juan et al., 2007; Muntadas et al., 2016). However, there were some unexpected results for two of the ranks considered less vulnerable to trawling: the abundance of the low vulnerability rank in maerl fishing grounds and the abundance of medium-low vulnerability rank in muddy fishing grounds. In both cases, these ranks were more abundant in untrawled fishing grounds than in trawled fishing grounds. This unexpected result could be due to a low specificity of the vulnerability ranks, and therefore, further work must be done in the future to define and integrate new BTs into the BTA, which may improve the definition. However, these analyses might be difficult due to the lack of information about news BTs of infaunal organisms with rarely studied biological characteristics (Bolam and Eggleton 2014).

Maerl and muddy fishing grounds

The variation in the specific compositions of infauna in maerl and muddy habitats implies variation in BT abundance, which could mean changes or loss of functionality at the habitat level (de Juan et al., 2007; Bremner 2008). In trawled maerl beds, highly vulnerable organisms, such as gastropods and polychaetes of the families Terebellidae, Paraonidae and Pectinariidae, appeared to have been replaced by other less vulnerable organisms, such as polychaetes of the Syllidae family (Kaiser et al., 1996; Sanchez et al., 2000; Simpson et al., 2006; de Marignac et al., 2009). In trawled muddy bottom habitat, the abundance of Sipunculids, bivalves and polychaetes of the family Capitellidae decreased, whereas less vulnerable organisms increased, such as polychaetes of the family Lumbrineridae, which proliferate in these environments due to their position under the substrate, among other reasons (Sanchez et al., 2000; Tiano et al., 2020). Each of these animals carry out specific functions in the habitat and has a specific nutritional composition that is important for the commercial species feeding on them (Lloret et al., 2007; Muntadas et al., 2014). Most polychaete species are bioturbators and deposit feeders or scavengers that oxygenate the sediment while also collecting nutrients deposited there from the water column, and bivalves are filter feeders that fix the nutrients suspended in the water column (Snelgrove 1997; Snelgrove et al.. 2014; Muntadas et al., 2016). For this reason, the substitution or loss of highly vulnerable species in maerl and muddy trawled habitats can lead to changes in the nutritional properties of infauna, thus affecting the food of upper links of the food chain that directly or indirectly depend on infauna (Lloret et al., 2007; Lloret and Shulman 2014; Bolam and Eggleton 2014).

In this way, the study of nutrient flow through the trophic chain with biomarkers, such as fatty acids, which has rarely been conducted in benthic habitats (Levi et al., 2005; Arechavala-Lopez et al., 2019), could provide a more accurate idea of food quality and the effects of trawling on different benthic habitats, providing relevant information to improve the management of exploited habitats (García-de-Vinuesa et al., 2020).

The different responses of the infaunal communities inhabiting maerl beds and muddy bottoms to the impact of trawling may be due to the natural variability of their infaunal communities. Very diverse and abundant communities, such as the infaunal maerl community, could have greater resilience to external stressors than the infaunal communities of muddy bottoms, which have less abundance and diversity (Coll et al., 2010; de Juan and Hewitt 2014; Demestre et al., 2017a,b). This is due to functional redundancy, which allows the same ecosystem functions to be fulfilled by several species with or without a taxonomic relationship. Therefore, when vulnerable species disappear, other less vulnerable species with similar functional characteristics can proliferate and restore functionality at the ecosystem level (Muntadas et al., 2016). These differences in the natural characteristics of each habitat should be taken into account to better direct the type of management necessary in each specific case.

On the other hand, different responses of the infaunal communities inhabiting maerl and muddy habitats to trawling could also be due to the differences in the fishing effort between habitats, which must also be taken into account for their management (Thrush et al., 1998; Collie et al., 2005; Atkinson et al., 2011; de Juan et al., 2020). Therefore, in the trawled maerl fishing grounds, there is moderate fishing effort because there is a seasonal closure for trawling from March to September, while in the trawled muddy habitat, the fishing effort is continuous and intense all year round and is only interrupted during the month of February, when a short temporal closure to trawling is implemented (García de Vinuesa et al., 2018). Differences in fishing effort can produce error when comparing vulnerability between habitats. In future studies, habitats with a history of very similar fishing exploitation should be compared. However, it is practically impossible to know the history of fishing effort in habitats that have been exploited by trawling for more than a century.

Implications for ecosystem management

Protecting marine ecosystem goods and services is one of the main objectives of European fisheries policy (EC 2008/56). However, the differences observed between the infaunal communities of trawled and untrawled fishing grounds indicate that trawl fishing activity could endanger the diets of commercial species, thus impairing the goods and services offered by the maerl and muddy habitats. The results of this study revealed important differences in the response of infaunal communities in these habitats. Therefore, based on their specific responses to trawling, the fishing effort that each habitat can support and their physical and biological characteristics, specific management measures should be implemented that help achieve the restoration and sustainable exploitation of each habitat.

Since 2008, the European commission has encouraged its member states to move towards ecosystem-based fisheries management (EBFM) (EC 2008/56); marine protected areas (MPAs) and temporary closures have proven useful and easy tools to implement (Harmelin-Vivien et al., 2008; Higgins et al., 2008; Kincaid et al., 2017; Corrales et al., 2020). In addition, the European Commission has implemented protection figures for non-renewable resources, such as banning trawling on maerl bed rodoliths (EU Directive 92/43/EEC; EU Council Regulation 1967/2006). However, EBFM is far from being implemented in the Mediterranean (Sartor et al., 2014), and the current trawling ban on maerl beds has no real effect because trawlers continue to exploit these habitats (Ordines et al., 2017; García-de-Vinuesa et al., 2018).

Even though the fishing effort carried out on the trawled maerl bed is limited to six months per year, we found important changes in the composition of infauna. Infaunal species substitution in maerl habitats can involve an irreversible loss of functionality, affecting fisheries resources. However, in addition to proposing management measures that affect maerl habitats, it must also be taken into account that the rodoliths that make up the maerl are considered a non-renewable resource due to their very slow growth; they are affected by trawling, which causes them to decrease in size and transforms the physical characteristics of the habitat, potentially transforming the infaunal community (Bordehore et al., 2003; Ordines et al., 2017). Therefore, in the case of maerl beds, the precautionary approach should drive its management so that to achieve a balance between the recovery of infaunal communities and sustainable exploitation of this habitat, it is recommended to carry out a spatial closure on trawling in maerl habitats through the establishment of MPAs, which would still allow other fishing methods that provoke less damage to the benthic environment, such as the use of trammel nets or longlines by small-scale fisheries (Martin et al., 2019). In contrast, the trawled muddy bottoms appeared seriously transformed in terms of loss of abundance and substitution of species due to the intense fishing effort that has been supported for decades. However, muddy bottoms do not have slow-growing biological structures like those of maerl beds, so fishery that allows trawling should be valued. Short temporal closures, such as the one that currently takes place in the trawled muddy bottom habitat (1-2 months), have been shown to have no positive effect on the recovery of muddy benthic communities (Sanchez et al., 2000; Demestre et al., 2008). Therefore, to restore the infaunal community in trawled muddy bottoms and attain sustainable exploitation in these habitats, it is recommended that temporal and spatial closures be implemented for longer durations.

The considerable differences in the specific compositions of the existing habitats in the Mediterranean Sea together with the very wide range of anthropogenic impacts to which they are exposed (Coll et al., 2010; Mouillot et al., 2013; Arechavala-Lopez et al., 2019; de Juan et al., 2020) requires that the study of habitat vulnerability be carried out individually for each impact to achieve management that efficiently integrates the procurement of goods and services with the conservation of habitats.

Acknowledgements

This study was carried out within the framework of the following research projects: CriMa (RTI2018-095770-B-100-MCIU/AEI/FEDER,EU), which is funded by the Ministry of Science and Innovation of the Spanish Government; the MINOUW (H2020-SFS-2014-2) project, which is funded by the EC (contract n° 634495); the GALP-Costa Brava Omega 3 project, which is funded by the European Maritime and Fisheries Fund (EMFF) and the D.G. Fisheries of the Autonomous Government of Catalonia and Cap de Creus projects, which are funded by La Caixa Foundation. We also thank the crew of the García del Cid, the trawlers and artisanal fishers for their help and university students for their collaboration of during their training activity.

Capítulo 4

Fatty acids as health indicators of exploited benthic habitats in the Mediterranean: the case of maerl beds and muddy bottoms

Fatty acids as health indicators of exploited benthic habitats in the Mediterranean: the case of maerl beds and muddy bottoms

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Bajo revisión: Estuarine, Coastal and Shelf Science

Abstract: Highly productive Mediterranean habitats such as maerl beds and muddy bottoms are subject to severe impacts from trawling. Fish species that inhabit these habitats, such as red mullet (*Mullus barbatus* and *M. surmuletus*) can achieve optimum condition with a diet of infaunal prey, which provides the diverse fatty acids (FAs) that are fundamental in shaping life history traits such as growth and reproduction. In this study, we have evaluated for the first time how trawling can affect the FA profile of red mullet and of their infaunal prey, as a result of trawl disturbance of maerl and muddy bottoms. We also discuss FA variations among habitats and how they can be used as trophic markers. In red mullet muscle from both maerl and muddy bottom habitats, we observed a higher concentration of C20:4n-6 (arachidonic acid, AA) and C16:0 (stearic acid) in untrawled areas compared to trawled areas and, in the case of maerl beds, untrawled areas also presented higher concentrations of C18:3n-3 (alfa-linolenic acid, ALA). The main FAs found in red mullet were the same as the main infaunal FAs. There was nearly 30% dissimilarity in the infaunal FA profile between trawled and untrawled maerl and muddy habitats. Our results support the idea of using FAs as an indicator of habitat health which can contribute to protecting the goods and services derived from these benthic ecosystems by helping to improve an ecosystem-based fishery management of them.

Keywords: fatty acids, trawling, maerl, muddy bottoms, red mullets, infauna.

1. Introduction

Trawling severely affects highly productive Mediterranean habitats such as maerl beds and muddy bottoms, producing a considerable physical impact on the seabed which reduces the abundance and diversity of benthic communities (Demestre et al., 2008; de Juan et al., 2011; Muntadas et al., 2016). These communities are essential components in the food chain which leads up to high-value commercial species (Kamenos et al., 2004; Muntadas et al., 2014). Maerl beds are accumulations of unattached calcareous rhodophytes, living and dead, found at depths of between 9 and 150 meters, with the average depth being 55m in the Mediterranean Sea (Basso et al., 2017). They form a heterogeneous, three-dimensional, hard substrate that fosters an especially diverse community (Ramos-Espla and Luque 2008); indeed, maerl beds are considered to be the second most diverse communities in the Mediterranean, after *Posidonia* meadows (Ballesteros 2006). Maerl beds are a non-renewable resource because of their slow rate of growth, and are therefore classed as Special Areas of Conservation in Annex I of the Habitats Directive (EU Directive 92/43/EEC). Furthermore, two of the main specimens forming these habitats, *Lithothamnion corallioides* and *Phymatolithon calcareum*, appear in Annex V of the Habitats Directive. Consequently, trawling is banned in areas of maerl beds by the European Union (EU council regulation 1967/2006). However, these vulnerable habitats are currently being affected by trawling in the northwestern Mediterranean (Ordines et al, 2017; García-de-Vinuesa et al., 2018) and there is a significant lack of information regarding their current distribution and their conservation status.

On the other hand, soft sediments, such as sand or mud, cover 70% of the world's sea floor (Snelgrove 1999). Although muddy bottom habitats are not as structurally complex as maerl bed habitats, they have been shown to be able to host extremely high species diversity (Coleman et al., 1997; Gray 2002) and to sustain benthic communities that provide fundamental ecosystem services (Thrush and Dayton 2002). In addition, they function as nurseries for important commercial species such as *Merluccius merluccius*, *Lophius spp.* and *Pagellus bogaraveo* (García-De-Vinuesa et al., 2018). However, trawling has been having a detrimental effect on muddy bottoms in the Mediterranean Sea for centuries (Delahoz et al., 2018), resulting in a decrease in the abundance and condition of the commercial species inhabiting them (see, for example, Tserpes et al., 2002; Lloret et al., 2007). Temporary closures of such areas to trawl fleets have been applied – up to a maximum of 2 months – but these have been shown to be inefficient as a means of increasing the abundance or diversity of the benthic species within them (Demestre et al., 2008).

Red mullets (*Mullus barbatus* and *M. surmuletus*) are among the main target species of Mediterranean demersal trawlers due to their abundance and economic value (Demestre et al., 1997; Tserpes et al., 2002). Both species have a wide bathymetric distribution in the northwestern Mediterranean. *M. surmuletus* is associated with shallow bottoms where maerl habitats are found at depths of between 9 and 150m, whereas *M. barbatus* is more abundant in muddy habitats at depths of between 25 and 200m (Lombarte et al., 2000; Basso et al., 2017). Both red mullet species feed mainly on infauna (Mahmoud et al., 2017) but there are important interspecific preferences regarding the heterogeneous taxa that make up the infauna. *M. barbatus*, inhabiting muddy bottoms, is able to dig more deeply in search of prey, so it usually feeds more on polychaetes (Ben-Eliahu et al., 1990), while the diet of *M. surmuletus*, inhabiting hard bottoms, such as maerl beds, includes a greater number of crustaceans such as amphipods, mysids and decapods (Machias and Labropoulou 2002). Therefore, variations in the abundance or diversity of these infauna communities – caused by natural or anthropogenic impacts – can affect the diet of these two commercial species which, in turn, affects their physical condition (Lloret et al., 2007).

Fatty acids (FAs) are fundamental for the health of fish and are obtained from their prey. They are essential nutrients and specific to many of their vital functions (Lloret et al., 2014) and therefore, knowing their concentration in particular marine areas give us an indication of the functional advantages to fish that feed there. Specifically, certain polyunsaturated fatty acids (PUFAs), such as C20:4n-6 (arachidonic acid; AA) and C18:3n-3 (alfa-linolenic acid; ALA) have a positive influence, for fish, on growth, larval development and oocyte quality (Sargent et al., 1995a,b; Almansa et al., 1999; Norberg et al., 2017), while others, such as C20:5n-3 (eicosapentaenoic acid; EPA) can enhance the reproductive potential of fish (Dalsgaard et al., 2003). Saturated fatty acids (SFAs) such as C18:0 (stearic acid), and monounsaturated fatty acids (MUFAs) such as C18:1 (oleic acid), are also found in high concentrations in fish and are important in other vital functions, such as energy reserves and oocyte development (Cowey et al., 1985; Weber et al., 2003; Dalsgaard et al., 2003).

FA transfer from prey to predator provides a snapshot of the most recently eaten food, so they have been used as biomarkers for the identification of trophic interactions (Dalsgaard et al., 2003; Fernandez-Jover et al., 2007). Furthermore, they may be useful in measuring the health status of habitats, although this has rarely been tested until now (Levi et al., 2005; Arechavala-Lopez et al., 2019). Specifically, no studies have yet been carried out on the use of FAs as indicators of the health of habitats exploited by trawling. Consequently, we propose an FA analysis of the two aforementioned species of red mullet and its infauna prey, with the aim of using it as an indicator of the health of habitats exploited by trawlers. Our purpose is to provide a new management tool that can contribute to the implementation of the ecosystem-based management approach espoused by the EU's Marine Strategy Framework Directive (MSFD) and to demonstrate the importance of the health of exploited stocks as an essential element of sustainable and profitable fisheries (Lloret et al., 2012).

In this context, the specific aim of the work is to investigate the effects of trawling on the health status of maerl and muddy bottom habitats as indicated by the fatty acid composition of red mullets and the infauna they feed on; we shall discuss the use of these fatty acid profiles as indicators of habitat quality and the trophic relationships within Mediterranean benthic ecosystems.

2. Material and methods

2.1 Study area

This study aimed to compare untrawled and trawled areas of two types of habitat: maerl beds (maerl) and muddy bottoms (mud). It was carried out in the North-Western Mediterranean (Fig 1) and samples were collected from four fishing grounds: two near Roses - one maerl bed (between 20 and 35m depth) and one muddy bottom (between 26 and 40m depth) - neither of which were affected by trawling, since only trammel nets are allowed; and two near Blanes - one maerl bed (depth between 54 and 107m) and one muddy bottom (depth between 70 and 113m) - both of which were affected by trawling. These four fishing grounds shall henceforth be referred to as untrawled maerl; untrawled mud; trawled maerl; and trawled mud.

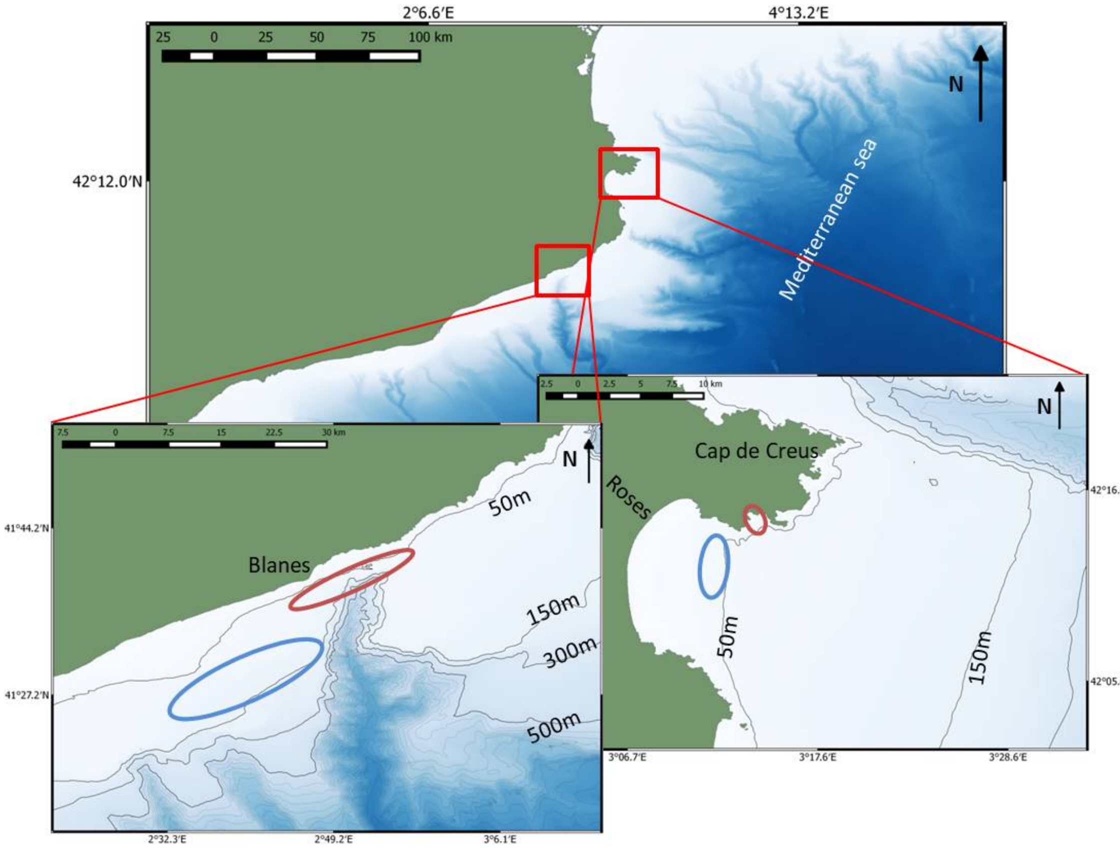

Fig 1.- Map of the study areas showing the trawled areas in Blanes (bottom left) and the untrawled areas in Roses (bottom right). Red ellipses correspond to maerl beds (maerl) and blue ellipses to muddy bottoms (mud).

2.2 Sampling procedure

Sampling activities were carried out in 2017 and 2018, always in the same months of the year to avoid seasonal effects on FA composition (Polat et al., 2007; Tufan et al., 2018).

2.2.1 Sampling of red mullets

We obtained a total of 114 specimens of red mullet: during October 2017, in the two untrawled areas (Roses), 68 specimens were caught in trammel nets (32 maerl and 36 mud); and during October 2018, in the trawled area (Blanes), 46 specimens were caught by trawlers (18 maerl and 28 mud). Due to the typical distribution of red mullets, the two different species were sampled only where each is most abundant: *M. surmuletus* in maerl beds and *M. barbatus* in muddy bottoms (see Table 1 for the details of the samples). Immediately after capture, the red mullet specimens were placed on ice, individually measured, and dissected to obtain the entire muscle tissue of each fish which was preserved in a liquid nitrogen container and subsequently frozen at -80 °C (within 6 hours of capture) until FAs were analyzed.

Table 1. Sampling features on the four fishing grounds selected, showing mean depth (MDepth), number of grabs (NG) for infauna, number of red mullet (NM), mean length (ML) and weight (MW) of individuals together with standard deviation (SD).

Fishing ground	MDepth (m)	NG	NM	ML (cm)	SD	MW (g)	SD
Untrawled maerl	20.5	15	32	19.83	3.13	94.92	44.93
Untrawled mud	26.5	15	36	18.71	1.1	84.7	18.73
Trawled maerl	72.5	15	18	22.83	2.73	167.06	72.83
Trawled mud	91	15	28	18.26	1.77	70.22	22.11

2.2.2 Sampling of infauna

The samples of infauna were obtained as follows: three random stations were selected at each of the four fishing grounds on the same seabeds from which the red mullet specimens were taken. In order to obtain the minimum sample size recommended (de Juan et al., 2007), five samples were obtained at each station, using Van Veen grabs; the infaunal organisms were immediately separated by stereoscope from the sediment and the organisms from the 5 grabs were collated into one sample. Thus a total of 60 grabs were made to produce a total of 12 collated samples: 6 in the untrawled Roses area (3 maerl, 3 mud) from a commercial trammel net vessel in October 2017 and 6 in the trawled Blanes area (3 maerl, 3 mud) during the DEEP VISION II oceanographic cruise carried out on the R/V "García del Cid" in October 2016. The organisms were preserved in tubes in a liquid nitrogen container and subsequently frozen at -80 °C (within 6 hours of sampling) following the same freezing process as for the red mullet muscle, until FAs were analyzed.

2.3 Analysis of FAs in muscle of red mullet and in the infauna

The FAs were analysed by gas chromatography coupled with a flame ionization detector (CG-FID) as prescribed in ISO 12966-4:2015, which specifies a method for the determination of FAs methyl esters (FAMEs) derived by transesterification or esterification from fats, oils, and FAs. CG-FID is one of the most widely used methodologies for separating and analysing dairy FAs in food.

A minimum of 40g of fish muscle per sample and a minimum 2g of infauna organisms per sample were used in the FA analyses. Each sample was homogenized with a liquidizer for 15 minutes with 50 ml of petroleum ether without heating; then, to evaporate the solvent, a R-210 Buchi rotary evaporator was used. The injection volume of samples and standards was 1µL and the column used was a high polarity capillary column, BPX 70, 70% cyanopropyl / polysilphenylene-siloxane column 0.25µm, 0.25mm ID and 30m using an Agilent 7693A gas chromatograph (Agilent Technologies USA).

The initial temperature was 90 °C for 1 min, then a ramp of 4 °C/min was first carried out until it reached 206 °C, and another of 20°C/min up to 246 °C and this temperature was then maintained for 5 min. The injector temperature was 260°C, and the detector temperature was 280°C. The total process lasted 37 minutes with an air flow of 400mL/min, an H2 flow of 30 mL/min and a Helium flow of 25 mL/min. Chromatographic peaks were integrated and identified using standard samples (Supelco 37 Component FAME Mix, from Sigma Aldrich). The content of each fatty acid in lipids was expressed as the percentage of the total content of all fatty acids. The limit of quantification was set at 0.1%.

2.4 Data analysis

From all of the 29 FAs we identified (supplementary Table S1 and S2), we selected those FAs that displayed high concentrations or were known to be involved in important physiological functions in fish. The mean percentage (and standard errors) for each of these FAs, in red mullet and infauna, were calculated for each fishing ground. In addition, in the case of the data on red mullet FAs, first a Shapiro-Wilk test was used to study data normality and then a Levene test for the homogeneity of variance. Non-compliance with parametric ANOVA assumptions led to utilization of the Kruskal-Wallis non-parametric test to evaluate differences in each FA of red mullet muscle (both species) from trawled and untrawled fishing grounds. When we found significant differences ($p<0.05$), we used a post hoc Pairwise Wilcoxon Rank Sum Tests to define where the differences were found. We also applied a Principal Components Analysis (PCA) as a clustering method on red mullet FAs in order to study the trawling effect by habitat. Finally, to study any dissimilarity between infauna samples from trawled and untrawled areas of both maerl and muddy habitats, a SIMPER procedure (PRIMER, Clarke & Warwick 1994) was carried out which accounted for 90% of the FA dissimilarity accumulated. Statistical analyzes were carried out using the statistical programs R 3.3.1 (R Development Core Team 2016) and PRIMER 6.1.2 (Clarke and Gorley 2006) for the principal component analysis (PCA).

3. Results

3.1 Effects of trawling on maerl beds

3.1.1 *Mullus surmuletus*

Significant ($p<0.05$) differences in the concentrations of several FAs were found in *Mullus surmuletus* muscle between trawled and untrawled maerl beds. The sum concentration of omega 6 (Σn-6), and the concentrations of ALA, stearic acid and AA were significantly higher in untrawled maerl than in trawled maerl (Table 2). On the other hand, a significant but opposite pattern was observed in the sums of saturated (ΣSFA), unsaturated (ΣUFA) and mono-unsaturated (ΣMUFA) fatty acids, as well as for oleic acid since in these cases, the concentration was significantly higher in the trawled maerl beds compared to the untrawled maerl beds.

The results of the PCA analysis showed that 71.9% of the total variation in the FA profile obtained from *Mullus surmuletus* muscle samples was explained by two principal components (PC1: 46.3%; PC2: 25.6%). PC1 is mainly explained by variation in C22:6n-3 (docosahexaenoic acid, DHA) and EPA while PC2 is mainly explained by the variation of oleic acid and DHA.

3.1.2 Infauna

According to the SIMPER analysis, the average dissimilarity between infauna samples from trawled and untrawled maerl was 28.99%. In the infauna from untrawled maerl, the highest concentrations of FAs found were, in decreasing order: palmitic acid (C16:0), oleic acid, EPA and stearic acid, all of which showed concentrations higher than 14% (Table 3). These were followed by AA and palmitoleic acid (C16:1) with concentrations of between 4 and 5%, and finally DHA, linoleic acid (C18:2n-6) and ALA, with concentrations of less than 4%. In the case of the infaunal FAs from trawled maerl, we found concentrations above 10% for EPA, oleic acid, palmitic acid and DHA; followed by concentrations of between 6.5 and 10% for palmitoleic acid, AA and stearic acid; and, finally, linoleic acid showed the lowest concentration at 3.98%.

Table 2. Composition of FAs in muscle of *M. barbatus* and *M. surmuletus* (mean percentage and standard error (S.E) for each FA at four fishing grounds. An asterisk (*) denotes statistically significant differences ($p<0.05$), which were obtained with Pairwise Wilcoxon Rank Sum Tests. The sums of saturated (ΣSFA), unsaturated (ΣUNS), monounsaturated (ΣMUFA), polyunsaturated (ΣPUFA), omega 3 (Σn-3) and omega 6 (Σn-6) fatty acids are also shown.

FAs	Trawled maerl		Untrawled maerl			Trawled mud		Untrawled mud		
	Mullus surmuletus					*Mullus barbatus*				
	Mean	SE	Mean	SE		Mean	SE	Mean	SE	
C16:0	19.95	0.32	20.24	0.36		20.83	0.83	20.58	0.90	
C18:0	4.97	0.28	6.18	0.43	*	4.55	0.20	7.03	0.23	*
ΣSFA	33.11	0.50	35.55	0.64	*	33.55	1.87	38.37	0.70	*
C16:1n-7	8.70	0.37	8.76	0.25		10.91	0.53	12.19	0.50	
C18:1cn-9	19.72	0.75	15.98	0.45	*	23.11	0.66	17.88	0.76	*
ΣMUFA	34.00	1.36	28.10	0.72	*	38.53	1.66	35.94	0.59	*
C18:2n-6	2.52	0.32	2.33	0.13		1.18	0.14	0.91	0.05	
C18:3n-3	0.80	0.20	1.10	0.09	*	0.53	0.07	0.31	0.03	
C20:4n-6	3.89	0.26	6.45	0.20	*	2.76	0.18	3.82	0.09	*
C20:5n-3	11.64	0.56	12.81	0.34		11.72	0.46	12.06	0.57	
C22:6n-3	15.20	0.92	12.63	0.75		9.92	0.75	6.74	0.22	*
ΣPUFA	34.20	0.91	36.25	0.89		26.58	1.72	25.43	0.68	
Σn-3	27.65	1.12	26.90	0.94		22.41	1.35	19.52	0.61	*
Σn-6	6.55	0.48	9.35	0.26	*	4.17	0.37	5.91	0.15	*
ΣUNS	68.20	1.31	64.35	0.59	*	65.11	3.38	61.37	0.76	*

3.2 Effect of trawling on Muddy bottoms

3.2.1 *Mullus barbatus*

When we compare the FAs found in *M. barbatus* from untrawled and trawled muddy bottoms, we find significantly higher concentrations of ΣSFA, omega 6, AA and stearic acid (Table 2) in the untrawled mud specimens; in contrast, there were higher concentrations of Σn-3 (omega 3), ΣUFA, ΣMUFA, DHA and oleic acid in the trawled mud specimens.

PCA analysis (Fig 2b) showed that 75.4% of the variance was explained by two PCs (PC1: 55.4; PC2: 20.1). PC1 was explained mainly by oleic acid variations, and PC2 was mainly explained of DHA and EPA variations.

3.2.2 Infauna

According to the SIMPER analysis, the average dissimilarity between infauna samples from trawled and untrawled mud was 25.67%. In untrawled mud we found concentrations above 17% of the following FAs: palmitic acid, EPA, palmitoleic acid and oleic acids (Table 3). Concentrations of stearic acid and linoleic acid were close to 6.5%, while those of DHA and AA were below 5%. In the case of trawled mud infauna, the concentration of palmitic acid and oleic acid was high, in excess of 25%. The concentration of EPA was 14.26% while those of stearic acid and palmitoleic acid were close to 8%. Finally DHA, linoleic and AA showed the lowest concentrations.

Table 3. Fatty acid (FA) composition of infauna (mean percentage and standard error (S.E) for each FA) from each of the four fishing grounds

FA	Trawled maerl		Untrawled maerl		Trawled mud		Untrawled mud	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
C16:0	18.00	2.58	26.40	1.50	27.16	7.28	21.36	1.85
C18:0	6.57	0.73	14.36	7.57	8.06	0.83	6.30	0.82
C16:1n-7	9.55	1.62	4.96	4.95	8.08	4.08	19.77	0.95
C18:1cn-9	18.41	4.42	22.54	5.05	29.98	0.43	18.97	0.49
C18:2n-6	3.98	0.18	3.39	2.07	4.13	2.17	6.45	0.85
C18:3n-3	0.01	0.00	0.52	0.51	0.01	0.00	0.01	0.00
C20:4n-6	7.68	1.94	4.45	4.44	2.98	2.97	3.44	1.79
C20:5n-3	19.11	2.82	17.77	0.72	14.26	5.45	17.69	1.39
C22:6n-3	10.12	1.53	3.90	2.25	5.35	1.82	4.63	0.74

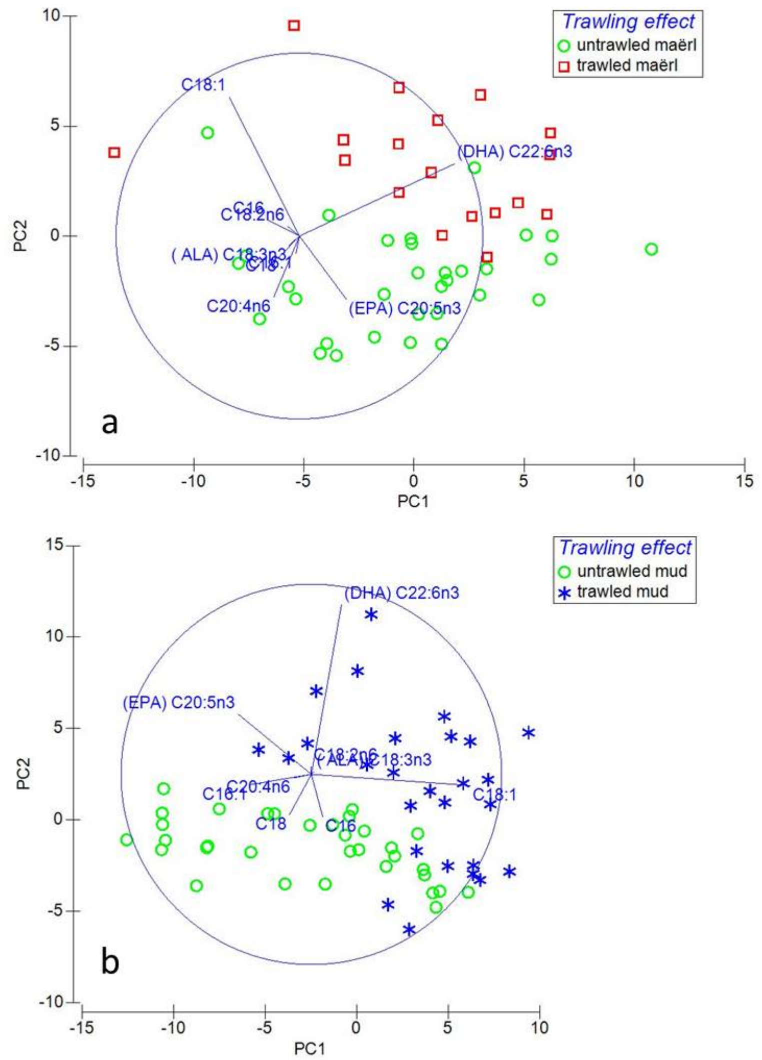

Figure 2.- PCA analysis of FA profiles of (a) *M. surmuletus* and (b) *Mullus barbatus* caught in trawled and untrawled zones of two different habitats (maerl beds and muddy bottoms) in the north-western Mediterranean Sea.

4. Discussion

Our results show that several of the infaunal FAs incorporated by red mullet were found in higher concentrations in untrawled areas than in trawled areas (maerl beds and muddy bottoms, in both cases). This indicates a potentially detrimental effect of trawling on the health of benthic habitats in addition to the reduced abundance and diversity among fish and infauna already observed in other studies (Demestre et al., 2008; Ordines et al., 2017). One of the consequences of this can be seen in the concentrations of polyunsaturated fatty acids (PUFAs) in red mullet muscle. AA, for example, was detected in greater concentration in red mullet muscle in untrawled areas than in trawled areas (both maerl and mud), as was the case with ALA (in maerl beds). This will boost the productivity of the stock of red mullet feeding in untrawled areas because AA has an important role in stress resilience, reproductive potential and larval development of fish (Sargent et al., 1999; Norberg et al., 2017) due to its involvement in a wide range of physiological processes in fish, such as blood coagulation, immune and inflammatory responses, cardiovascular tone, and renal and neuronal functions (Schmitz and Ecker 2008). The higher concentrations of ALA found in untrawled maerl will also be advantageous because this PUFA is necessary for the growth of juveniles and for oocyte quality (Sargent et al., 1995a,b; Almansa et al., 1999). In the case of the SFAs, stearic acid was found in higher concentrations in red mullet from untrawled maerl and mud than in comparable trawled habitats. Stearic acid has been shown to improve energy reserves in the oocytes of fish (Cowey et al., 1985) and so this would be advantageous in relation to the reproductive potential of fish inhabiting untrawled habitats.

However, for some of the other important FAs, the situation was reversed. For example, concentrations of red mullet DHA were higher in trawled mud than in untrawled mud areas. In line with our results, a recent study carried out in the North-western Mediterranean showed significantly higher DHA concentrations in octopus caught in areas with high anthropogenic impacts than in those caught in a marine reserve where such impacts were lower (Arechavala-Lopez et al., 2019). Further study of this spatial pattern of DHA – linked to anthropogenic impacts – should be undertaken to understand why higher concentrations of certain PUFAs are found in animals in areas impacted by human activities, since PUFAs are fundamental in the physiological processes of fish (Sargent et al., 1995a,b). Furthermore, MUFA levels in mullets were significantly higher in trawled areas than in untrawled areas, fundamentally due to the contribution of oleic acid (which was significantly higher in trawled areas). It has been proven that higher concentrations of MUFAs, such as oleic acid, are essential for the growth of fish and contribute to the energy storage necessary before fish reproduction (Ronnestad et al., 1994; Weber et al., 2003). However, it has been observed that where dietary sources of omega 3 and omega 6 are scarce, and a high level of oleic acid is present, the two PUFAs can be replaced by significant concentrations of oleic acid in fish tissues (Ibeas et al., 1996). This is also in line with our results since we found lower concentrations of omega 6 in trawled maerl and muddy habitats than in comparable untrawled habitats. Hence, the higher oleic acid concentrations found in our study could be offsetting the lack of omega 6 in trawled habitats; considering the important functions of some omega-6 PUFAs, such as AA, this could be detrimental to the condition of red mullet in trawled habitats. It must also be considered that red mullet undertake seasonal migrations and these movements may be driven in part by the search for optimum FAs. These red mullet migration patterns are well known: in spring they head for shallower areas for reproduction and then migrate to deeper areas after recruitment in autumn (Aguirre 2000). Since the FA requirements of fish vary at different development stages (Tocher 2010), we hypothesize that the seasonal migratory behavior of red mullet could be influenced by the availability of prey that can supply certain FAs in different seasons. Furthermore, although all our samples were collected in the month of October to avoid any seasonality effect, it must be taken into account that depth could be a factor that may have led to some error in this study since the untrawled areas were shallower than the trawled ones.

Of the FAs found in infauna, as with those found in red mullet muscle, the highest concentrations were those of palmitic acid, oleic acid, EPA, palmitoleic acid, stearic acid and DHA, and the dissimilarity between FA composition in samples from trawled and untrawled maerl and muddy bottom habitats presented a very similar range (between 25-29%). In addition, the concentrations of some FAs (ALA, DHA, AA, stearic and oleic acid) followed a similar pattern, in terms of trawled and untrawled areas, to the one found in red mullet. There have been few studies into the composition of FAs of infauna animals, the majority of which focused on polychaetes for aquaculture purposes, and reported large concentrations of PUFAs, with EPA being the most abundant (Palmer et al., 2014; Moussa Dorgham et al., 2015), as was the case in our study. This similarity with our results is likely explained by the fact that the most abundant animals among the infauna we analyzed were polychaetes.

EPA – which is important in reproductive functions in fish (Sargent et al., 1995a,b) – and other fatty acids found in infauna, such as DHA, AA, ALA – which are crucial in various functions in fish – are classed as essential fatty acids (EFAs) and can only be obtained by fish through food (Hastings et al., 2001). The infaunal communities that make up the mullet diet can be very diverse (Mahmoud et al., 2017), but it has been shown that certain infaunal species – those more vulnerable to the impact of trawling – largely disappear from habitats that are highly disturbed by trawling and, as a result, the abundance and diversity of these infaunal communities decreases (de Juan et al., 2007; Muntadas et al., 2016; Demestre et al., 2017). Our results can be explained by the fact that the FA concentrations we observed in red mullet depend on the FA variation in the available prey (infauna) which, in turn, is severely impacted by trawling. There have been other studies, carried out in the western Mediterranean, that have concluded that the bottom trawling effort was not, in fact, the main factor in the differences in maerl-forming algae and other red algae (Barbera et al., 2012; Moranta et al., 2014). However, our results show that trawling does have a detrimental effect on the health of maerl beds by altering the FA profile of both infauna and fish, and this is in line with reports of the negative effects of trawling on abundance, biomass and diversity of maerl forming species and other red algae in the Balearic Islands (Ordines et al., 2017).

Our results also show differences in the infaunal and red mullet FA profiles between the two habitats – maerl beds or muddy bottoms – regardless of trawling activity. The FA profiles of *M. surmuletus* and the infauna from maerl habitats were both characterized by high concentrations of PUFAs: DHA, ALA and AA. In muddy bottom habitats, in contrast, *M. barbatus* and the infauna showed high concentrations of MUFAs, such as oleic and palmitoleic acids. Differences in FA profiles between habitats have already been reported in fish from the Mediterranean Sea (Levi et al., 2005). The differences we found in the red mullet FA profiles between habitats may derive from the natural variability in infaunal communities and their consequences up the trophic food chain, since infauna and *Mullus surmuletus* from maerl beds had very similar FA profiles, as did infauna and *M. barbatus* from muddy bottoms. Maerl infaunal communities are composed mainly of polychaetes, especially those from the Syllidae family, which are strongly associated with hard substrates (Rose and Pleijel 2001), and amphipod crustaceans, which find shelter among the hiding places in the three-dimensional assemblage of the maerl beds (Basso et al., 2017). Muddy bottom infaunal communities are also largely composed of polychaetes, albeit with different species, and there is a greater abundance of bivalves (Demestre et al., 2017).

Finally, with regard to the trophic relationship between red mullet and the infauna, we would point out that the principle FAs we found in each of these components of the food chain were the same and similar variations in relation to trawling and habitat were found. FAs have been used for more than four decades as qualitative markers to trace or confirm predator-prey relationships in the marine environment (Dalsgaard et al., 2003) and our results establish, for the first time, the predator-prey relations between red mullet and infauna. We therefore propose using FAs as biomarkers in the study of the structure and dynamics of red mullet food webs, as has been done with other fish species, such as *Trachurus mediterraneus* (Fernandez-Jover et al., 2007) and anchovy (Teodosio et al., 2017), and in attempts to identify key processes impacting the dynamics of benthic ecosystems (Dalsgaard et al., 2003). In our study, the FAs analyzed were obtained from all the different infaunal organisms together and to achieve a more accurate resolution of different FAs from different infauna organisms, future studies should focus on more specific taxonomic levels to determine more accurate trophic relationships between fish and their food.

Conclusions

The results from this study provide, for the first time, clear evidence that trawling has the capacity to affect the FA profile of fish and infauna inhabiting maerl beds and muddy bottoms; they also show that these FAs can be used as bioindicators of habitat health. FAs are key variables in the assessment of fish health because they can influence key population-level processes, such as natural mortality, reproduction, and growth (which, in turn, affect stock productivity). Our results help to understand how the health of exploited fish stocks is affected by anthropogenic impacts, and to establish links between fish health and the management of marine fisheries (Lloret et al., 2012). In this sense, the cessation or restriction of trawling activity in habitats where fish can obtain high quality nourishment from prey that has higher concentrations of certain FAs can contribute to protecting their value as goods and services and move towards an ecosystem-based system of fishery management. From the results of this work, we would suggest that maerl beds need to be closed to trawling and be exploited only by small-scale fisheries using longlines or trammel nets, which do not have a significant impact on the seabed. Urgent management measures aiming to preserve maerl beds from trawling have been strongly recommended recently in our study area and in the Balearic Islands (Ordines et al., 2017; García-de-Vinuesa et al., 2018). On the other hand, in areas of muddy sediments, short (1-2 months) closures to trawlers have been shown to be insufficient for benthic community recovery in the western Mediterranean (Demestre et al., 2008). It therefore appears that an increase in the duration of these seasonal closures or even his transformation in temporary closures of longer duration is needed to improve the condition of infauna by improving their overall FA composition and, subsequently, the condition of commercial species.

Acknowledgements

This work was carried out within the framework of the following research projects: the CriMa project (RTI2018-095770-B-100; MCIU/AEI/FEDER/UE); the MINOUW project (H2020-SFS-2014-2), funded by the EC (contract nº 634495); the Cap de Creus project funded by *La Caixa* Foundation, and the GALP-Costa Brava Omega 3 project co-funded by the European Maritime and Fisheries Fund (EMFF) and the D.G. of Fisheries of the Autonomous Govt of Catalonia. We would also like to thank the crew of the *García del Cid* vessel and the trawler and artisanal fishermen who were indispensable in achieving the objectives of this work.

Capítulo 5

Resumen de los resultados

De la consecución de los objetivos de esta tesis se desprenden los resultados que citamos a continuación. En primer lugar se han **identificado ecosistemas bentónicos especialmente productivos mediante la caracterización del descarte de la pesca de arrastre y se ha cuantificado el impacto pesquero al que se ven sometidos (capitulo 1)**. Encontramos 5 hábitats diferenciados entre sí. Un fondo de fango que engloba 2 caladeros, "Las 40" y "Capets", con características muy similares, ya que se encuentran a continuación el uno del otro, situados entre los 70 y 113 metros de profundidad. Su descarte estuvo compuesto por gran cantidad de equinodermos como el crinoideo *Ophiura texturata*, los erizos de mar *Echinaster sepositus* y *Echinus melo*, y peces óseos como bogas (*Boops boops*) y chuclas (*Spicara sp.*). También se descartaron individuos de especies comerciales por debajo de su MCRS (Talla legal) como la merluza (*Merluccius merluccius)*, o el rape (*Lophius spp.)*. El esfuerzo pesquero sobre este hábitat fangoso, fue continuado durante todo el año siendo especialmente intenso entre los meses de julio y noviembre. Encontramos otro fondo de fango en el talud, situado entre 195 y 493 metros de profundidad, formando parte de un caladero llamado "Malica" donde la especie objetivo de la flota de arrastre es la cigala (*Nephrops norvegicus)*, que fue también su principal descarte, en términos de abundancia, debido a su pequeño tamaño. Aquí, el esfuerzo pesquero fue también continuado aunque más intenso que en "Las 40" y "Capets", intensificado entre mayo y junio coincidiendo con el periodo de reclutamiento de la cigala. Un hábitat mixto de fango y agregación de crinoideos fue hallado en el caladero "La Planasa" situado entre 85 y 530 metros de profundidad, ya que su parte más profunda cae por la ladera de un cañón submarino y cuyo descarte presentó principalmente equinodermos, como el crinoideo *Leptometra phalangium y* el erizo de mar *Gracilechinus acutus,* e individuos de especies con tallas por debajo de su MCRS como merluzas o jureles (*Trachurus trachurus)*. Este caladero estuvo sometido a un esfuerzo de pesca continuo durante todo el año. Misma dinámica del esfuerzo pesquero se presentó en el caladero "Fluviana", localizado en el borde de la plataforma continental, entre 93 y 144 metros de profundidad, el cual describimos como un hábitat de agregación de crinoideos, por la gran abundancia de *Leptometra phalangium* descartada ya que supuso casi la mitad del total de animales descartados. En "Fluviana" también se descartaron merluzas, pageles y rapes con tallas por debajo su MCRS. Por último, encontramos un hábitat de maërl en un caladero llamado "Garotes", situado entre 54 y 107 metros de profundidad. Aquí se descartaron gran cantidad de rodolitos y especies de peces óseos como bogas, chuclas o salmonetes, algunas por debajo de su MCRS. El esfuerzo en Garotes fue marcadamente estacional ya que existe una veda estacional que cubre desde marzo a septiembre. El mayor esfuerzo pesquero observado se dio en septiembre y octubre coincidiendo con el final de la veda y la época del reclutamiento de una las principales especies objetivo de este caladero, el salmonete.

A partir de resultados obtenidos en el capítulo 1, elegimos especies representativas del descarte de hábitats de crinoideos y fondos de fango para **evaluar su supervivencia al descarte (capitulo 2a).** Para ello, estudiamos *in situ* y en los acuarios del ICM dicha supervivencia a partir de la evaluación de su estado de vitalidad. Todas las especies seleccionadas para el estudio, fueron invertebrados bentónicos. En general, su supervivencia fue elevada, llegando en muchos casos a valores del 100%. Además, encontramos una relación significativa entre la duración de la pesca de arrastre y la supervivencia de los individuos descartados, siendo esta menor cuanto mayor fue el tiempo de arrastre. Así, el crinoideo *Leptometa phalangium,* que es la especie más abundante en los fondos de crinoideos, mostró un 92.11% de supervivencia tras 96 horas de mantenimiento en acuarios. Otras especies frecuentes en este hábitat como el crinoideo *Antedon mediterranea*, el erizo de mar *Cidaris cidaris* y la estrella de mar *Echinaster sepositus* mostraron 100% de supervivencia también tras 96 horas de experimentación. En los fondos fangosos, el crustáceo *Dardanus arrosor* mostró 100% de supervivencia tras 96 horas de experimentación. Solo unas pocas especies de los fondos fangosos que fueron estudiadas a bordo, mostraron media o baja supervivencia (<32%). Entre ellas cabe destacar los crustáceos *Medorippe lanata, Parapenaeus longirostris, Solenocera membranacea, Squilla mantis, Munida intermedia y Pagurus excavatus*. Por otro lado, la cigala *Nephrops norvegicus* mostró una supervivencia a bordo que fue desde 15,61%, en la zona del talud del mar Tirreno, hasta un 55.25% en el talud del Mar Catalán.

Considerando los resultados obtenidos acerca de la supervivencia de la cigala en el capítulo 2a, el hecho de que la cigala es la especie más abundante del descarte en el hábitat fangoso del talud de Blanes, su alto valor comercial y que existe una exención a la obligación de desembarque para especies con MCRS que demuestren alta supervivencia al descarte, **se llevó a cabo un estudio estacional para la supervivencia al descarte de la cigala (capitulo 2b)**. Para ello, utilizamos un sistema de valoración específico de su estado de vitalidad, y una duración de 14 días de experimentación en los acuarios. El estudio mostró alta supervivencia con un 43% de media, mostrando una significativa variabilidad estacional, siendo esta supervivencia máxima en invierno (74%), media en primavera (36%) y mínima en verano (6%).

Tras el estudio de supervivencia del descarte y para tener en cuenta como esta pesca afecta a especies que no son capturadas, se llevó a cabo un estudio **en el que evaluamos y comparamos la vulnerabilidad a la pesca de arrastre de comunidades de infauna procedentes de hábitats de maërl y fondos de fango (Capitulo 3).** Para este estudio se seleccionaron 4 caladeros. 2 afectados por la pesca de arrastre, situados sobre un hábitats de maërl y un fondo de fango en el área de estudio de Blanes y 2 no afectados por la pesca de arrastre, situados sobre un hábitat de maërl y fondo de fango en el área de estudio de Roses. Respecto a los hábitats de maërl, fue significativamente menor la abundancia de especies categorizadas como de muy alta vulnerabilidad en el caladero afectado por la pesca de arrastre, que en el protegido de la pesca de arrastre. Sobre los fondos fangosos, se encontró una mayor abundancia de las especies con muy alta y medianamente baja vulnerabilidad en el caladero no arrastrado respecto al caladero arrastrado, y mayor abundancia de las especies categorizadas como de baja y muy baja vulnerabilidad en el caladero arrastrado respecto del protegido de la pesca de arrastre.

Sobre estos mismos 4 caladeros situados sobre hábitats de maërl y fondos de fango, también **se estudió la composición de ácidos grasos de salmonetes y de sus presas (infauna), a fin de evaluar la calidad y el estado de conservación de dichos hábitats (capitulo 4)**. Tanto para hábitats de maërl como para fondos de fango, en el músculo de salmonetes se encontraron mayores concentraciones de algunos ácidos grasos como el araquidónico (AA) y esteárico, y menores concentraciones de ácido oleico, en zonas no arrastradas respecto de zonas arrastrados. En zonas de maërl no arrastrado se encontró mayor concentración de ácido alfa-linolenico (ALA) que en las zonas de maërl arrastrado, así como mayores concentraciones de ácido docosahexaenoico (DHA) en el fondo de fango arrastrado respecto del protegido del arrastre. Los ácidos grasos mayoritarios de la infauna fueron los mismos que los de los salmonetes y mostraron un patrón similar de concentración respecto a la pesca de arrastre. Por último, encontramos diferencias de ácidos grasos esenciales como el DHA entre hábitats de maërl y fondos de fango, ya que se encontraron concentraciones superiores en los hábitats de maërl.

Discusión global

A lo largo de las últimas décadas, se ha evidenciado el efecto negativo que la pesca de arrastre tiene sobre los ecosistemas bentónicos (Thrush y Dayton 2002; Sommer 2005; Ordines et al., 2017), impactándolos de tal manera que reduce su complejidad física y biológica, disminuyendo la abundancia y diversidad de especies y comunidades bentónicas que los habitan, lo cual en último término, afecta a su funcionalidad. Estos efectos sobre los organismos bentónicos, tienen repercusión a nivel de las especies comerciales ya que ocasionan una disminución de su disponibilidad de alimento, afectando en así al estado de los estocs explotados (Lohrer et al., 2004; Lloret et al 2007; Muntadas et al., 2015, 2016). Ahondar en el conocimiento de este impacto es fundamental para llevar a cabo una correcta gestión de esta pesquería y de los hábitats que la sustentan. Pero la complejidad y singularidad de cada hábitat marino, así como la complicada dinámica de explotación de la pesca de arrastre, debido en gran medida a su multiespecificidad, hace que las respuestas de comunidades y especies ante su impacto, sean difíciles de interpretar (Levin y Lubchenco 2008; Koch et al., 2009). Ante esta problemática, para toda gestión pesquera debería de aplicarse el principio de precaución, que nos indica que en caso de amenaza para el medio ambiente en una situación de incertidumbre científica se deben tomar las medidas apropiadas para prevenir el daño (Escalante 2005). Para ahondar en el conocimiento de la respuesta de los hábitats ante la pesca de arrastre, necesitamos conocer cómo responden ante un nivel de impacto concreto las especies y comunidades particulares que los habitan (Kaiser y Spencer 1996; Collie et al., 2005; Kaiser et al., 2006). En este contexto, para avanzar en el conocimiento del estado de conservación y la vulnerabilidad a la pesca de arrastre que presentan hábitats especialmente productivos del mar Mediterráneo, en esta tesis se estudió su localización, se cuantificó el impacto pesquero al que se ven sometidos y se utilizaron varios indicadores novedosos: (i) la supervivencia de invertebrados al descarte, (ii) la vulnerabilidad a la pesca de arrastre de las comunidades de infauna y (iii) los ácidos grasos de los peces que viven en estos hábitats, tomando como ejemplo los salmonetes (*Mullus spp.*), y de sus presas. Atendiendo a los resultados obtenidos, en esta discusión se recomiendan medidas de gestión adecuadas para alcanzar en cada hábitat estudiado, un equilibrio entre conservación y explotación.

1. Localización y caracterización de hábitats mediterráneos especialmente productivos: la base para mejorar su gestión.

El primer paso para gestionar correctamente cualquier hábitat, es conocer su localización (Martin et al., 2014; Demestre et al., 2015). Sin embargo, la falta de información acerca del patrimonio biológico del Mediterráneo es preocupante, ya que faltan por localizar y delimitar gran parte de sus hábitats (Basso et al., 2017; Leonard et al., 2020). El trabajo de localización de hábitats marinos puede ser muy complejo, aún más al localizarse a profundidades que, para su muestreo, precisan de tecnologías complejas y económicamente costosas como la robótica submarina (Devine et al., 2020). En este sentido, sería lógico centrar los esfuerzos del trabajo de localización, en los hábitats que sean prioritarios para su conservación. Esta prioridad puede venir dada entre otras razones porque: (i) estén recibiendo impactos que podrían degradarlos irreversiblemente debido a la vulnerabilidad de las especies que los componen, como sucede con los hábitats de maërl, ya que están considerados un recurso no renovable (Ballesteros et al., 2019), (ii) nos brinden bienes y servicios esenciales en forma de aporte de alimentos que podrían estar en peligro, como los hábitats de crinoideos o ciertas zonas de los fondos fangosos (Gray 2002; Colloca et al., 2004). Para lograr hacer más extrapolable la técnica de localización de hábitats marinos prioritarios, en esta tesis buscamos otras herramientas menos complejas y costosas que el uso de robótica submarina. Concretamente, se usó con éxito el estudio del descarte de la pesca de arrastre tal y como se detalló en el capítulo 1. Por este motivo se recomienda **el uso de la caracterización del descarte en otras zonas explotadas por la pesca de arrastre en el Mediterráneo para la identificación y localización de hábitats de conservación prioritaria.** Sin embargo, hay que tener en cuenta que esta herramienta requiere de personal especializado y formado en campos científicos clave para la realización de campañas pesqueras, y de la colaboración de los pescadores. Además, si se quisiera extrapolar a todo el Mediterráneo, sería necesario un sistema común de muestreo y de tratamiento de datos en diferentes países y regiones. Y aunque el esfuerzo económico y logístico para las administraciones de los países ribereños sería moderado, este *modus operanding* podría verse dificultado en ciertas zonas del Mediterráneo, debido a los diferentes regímenes políticos existentes (Caddy 2012; Spagnolo 2012). También hay que tener en cuenta que este sistema de localización tiene limitaciones a la hora de delimitar los hábitats, ya que en ocasiones las zonas de pesca pueden no comprender todo el hábitat, o el arte de pesca puede muestrear de una sola vez distintos hábitats solapados.

La localización debe realizarse a partir de una buena caracterización del hábitat. En este sentido el estudio del descarte de la pesca de arrastre también se antojó una buena herramienta, ya que a partir de la clasificación y toma de medidas como la talla de los individuos muestreados, se puede contribuir a identificar hábitats esenciales para peces (en inglés EFH, de “Essential Fish Habitats”) (Auster y Langton 1998; Colloca et al., 2009; Massi et al., 2016). En el caso concreto de esta tesis, se localizaron EFH de maërl, de agregación de crinoideos y de fango, que funcionan como zonas de alevinaje de especies comerciales. Por este motivo, y teniendo en cuenta las particularidades de cada hábitat, en esta tesis **se recomiendan dos tipos de actuaciones para mejorar su gestión:**

a) El establecimiento de Áreas Marinas Protegidas (AMPs) sobre fondos de maërl. Esta recomendación viene dada por varios motivos: (i) el maërl está considerado un recurso no renovable (Barberá et al., 2003; Basso et al., 2017), (ii), fue identificado en esta tesis como EFH para importantes especies comerciales como los salmonetes, *Mullus barbatus* y *M. surmuletus*, y (iii), ni la prohibición de la pesca de arrastre sobre ellos (EU Council Regulation 1967/2006), ni su inclusión en los anexos I y V de la directiva hábitats de la Unión Europea han conseguido que cese la pesca de arrastre sobre ellos. Un sistema de AMPs ecológicamente representativo, bien conectado y gestionado de manera efectiva tiene beneficios ecológicos y ambientales, además de beneficios sociales y económicos (de la Torriente et al., 2019). Las AMPs han demostrado ser una herramienta de fácil implementación (Harmelin-Vivien et al., 2008; Higgins et al., 2008). Son útiles para la protección de hábitats y de las especies, ya que contribuyen a una mejor reproducción, reclutamiento y crecimiento de las especies de peces, contribuyendo así a aumentar la biomasa de la fauna bentónica, conduciendo a una comunidad más compleja y estructurada (Corrales et al., 2020). Pero hay que tener en cuenta que debido al cierre de zonas a la pesca mediante AMPs, la flota de arrastre podría dirigir su esfuerzo a los límites de la AMP o aumentarlo en otros caladeros, un trasvase de esfuerzo pesquero que podría tener un efecto negativo sobre esas otras zonas (Whitmarsh et al., 2002). Al haber menos zonas de pesca podría incluso derivarse conflictos entre los propios pescadores de arrastre o con la flota artesanal, que disputarían los recursos (Martín et al., 2019). Además, se ha relacionado el efecto del tamaño de la AMP sobre las especies comerciales, y se ha visto que el tamaño de la AMP tiene que ser lo suficientemente grande para suponer un beneficio a las áreas colindantes mediante la exportación de recursos pesqueros por medio de conectividad entre zonas (de Juan et al., 2012; Corrales et al., 2020).

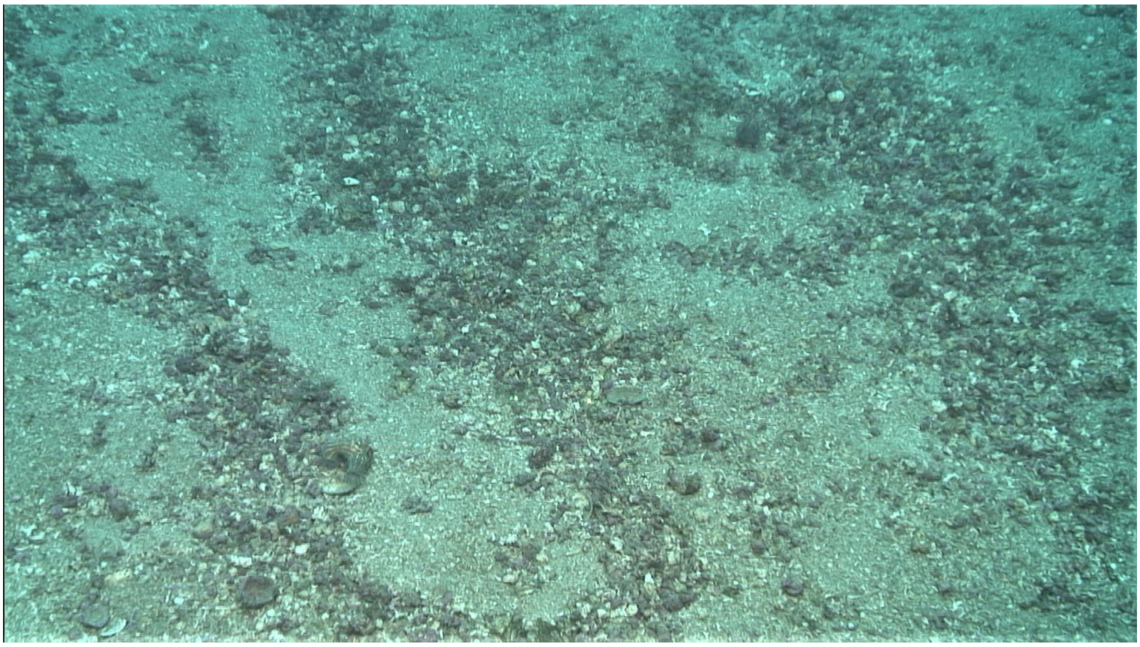

Figura 1. Hábitat de maërl localizado con el ROV Liropus 2000, durante la campaña del proyecto CriMa, llevada a cabo en el B/O Sarmiento de Gamboa (septiembre de 2020).

b) El establecimiento de vedas temporales de larga duración en hábitats de agregación de crinoideos y ciertas áreas de los fondos de fango. Ambos hábitats fueron caracterizados en esta tesis como zonas de alevinaje para especies de interés comercial como la merluza (*Merluccius merluccius*) o los rapes (*Lophius piscatorius* y *L. budegassa*), no son hábitats tan vulnerables a la pesca como los de maërl, pero los cierres estacionales de corta duración, como los que se realizan de un solo mes en la zona de estudio, se han mostrado poco exitosos en lo que ha recuperación de poblaciones del bentos se refiere (Demestre et al., 2008; Sciberras et al., 2013). La duración que deben tener estas vedas temporales debe calcularse en próximos estudios, atendiendo a las características particulares de cada hábitat. Estas vedas temporales son una alternativa a la reducción del esfuerzo pesquero en toda el área de pesca: un estudio reciente en el Mediterráneo estimó que, para lograr el rendimiento máximo sostenible de estocs de especies comerciales explotadas por los artes demersales, la disminución del esfuerzo pesquero debería ser superior al 80%, lo que en la práctica se vislumbra irrealizable (Martín et al., 2019). Como alternativa al cierre temporal, se podrían alargar las actuales vedas estacionales situándolas en los meses del año en los que se concentran los juveniles de especies comerciales. Esto serviría para asegurar el crecimiento de los juveniles de ciertas especies comerciales, pero sería difícil de ajustar a la biología de todas las especies objetivo en una pesquería multiespecífica como la pesca de arrastre (Samy-Kamal et al., 2015), y no tendría en cuenta la biología de especies no comerciales que sufrén de igual modo el impacto del arrastre. Además, hay que tener en cuenta que en la realización de vedas estacionales se suele observar un mayor esfuerzo pesquero en la zona protegida tras su apertura (Sys et al., 2017). Por el contrario, largos periodos de cierres temporales podrían ayudar a recuperar los estocs de especies comerciales sobreexplotadas como ya atestigua un estudio sobre el bacalao (*Gadus morhua*) en Canadá (Kincaid et al., 2017).

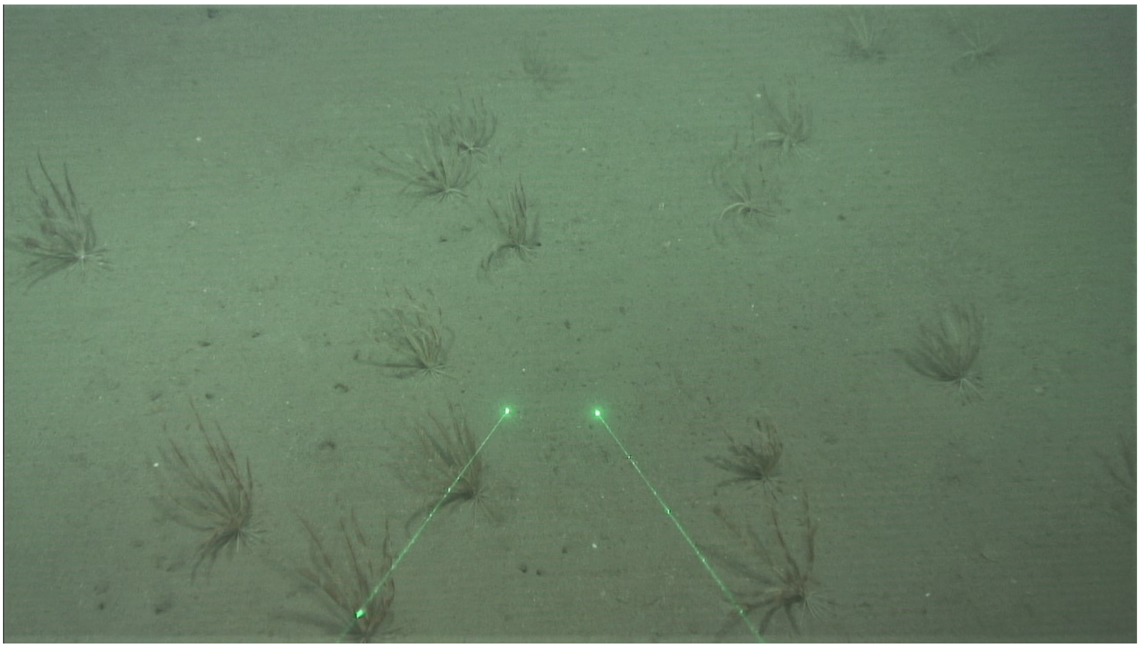

Figura 2. Hábitat de agregación de crinoideos localizado con el ROV Liropus 2000, durante la campaña del proyecto CriMa, llevada a cabo en el B/O Sarmiento de Gamboa (septiembre de 2020).

2. Sistema de monitoreo de embarcaciones (VMS): una herramienta especialmente útil para la gestión pesquera.

Tras la localización de los hábitats. El siguiente paso para su correcta gestión, debe ser la cuantificación del esfuerzo pesquero que estos soportan, ya que el estado de conservación de los ecosistemas bentónicos está fuertemente relacionada con dicho esfuerzo (Salas et al., 2004; Atkinson et al., 2011; de Juan y Demestre 2012). Para conocer este esfuerzo pesquero y relacionarlo con el estado de conservación del hábitat, necesitamos conocer las características de la flota y sus movimientos (Branch et al., 2006; Jennings y Lee 2012), puesto que se sabe que los pescadores varían de caladero en base a los cambios en la abundancia de especies objetivo, las condiciones meteorológicas y los cambios en el mercado (Martin et al., 2014). Los datos VMS se han mostrado útiles en este aspecto, ya que nos informan con bastante precisión en el tiempo y en el espacio de los movimientos de cada embarcación, por lo que a partir de ellos y conociendo la localización de los hábitats frecuentados y sus características, podemos identificar áreas y periodos de tiempo prioritarios para la gestión de la pesca (Jennings y Lee 2012; Martin et al., 2014; Demestre et al., 2015). Estos sistemas para la obtención de datos de esfuerzo pesquero son obligatorios en el Mediterráneo para embarcaciones de más de 15 metros de eslora (EU Regulation 404/2011). Su análisis a pequeña escala (1km^2), tal y como se ha llevado a cabo en esta tesis, permite una precisión suficiente como para el estudio de hábitats concretos, por lo que pueden ser una herramienta muy útil para la gestión pesquera (Blyth et al., 2004; Muntadas et al., 2015). Para un mejor uso del sistema VMS en el mar Mediterráneo, habría que tener en cuenta las características de la flota de arrastre de esta región. Esta flota pesquera en ocasiones es considerada como una flota pesquera semiindustrial debido al pequeño tamaño (menores de 15 metros) de muchas de sus embarcaciones (Lleonart et al., 1998; Martin et al., 2014), por lo que no están obligadas a integrar el sistema VMS. Además, estas embarcaciones de arrastre con esloras inferiores a 15 metros, faenan la mayoría del tiempo en las zonas de la plataforma continental donde encontramos los hábitats más productivos y diversos, y donde por lo tanto, la pesca de arrastre se vuelve menos selectiva (García-De-Vinuesa 2012; Tsagarakis et al., 2014). Por estos motivos, el VMS en el Mediterráneo no exprime todo su potencial ya que ignora parte de los movimientos llevados a cabo por un importante número de embarcaciones de arrastre de pequeña eslora, por lo que **la implementación obligatoria del VMS para toda la flota de arrastre, inclusive los barcos pequeños de <15 m de eslora, es muy necesaria.**

Los datos del VMS junto con datos de desembarque de capturas han sido utilizados para conocer la distribución espacial de especies objetivo (Fonseca et al., 2008; Gerritsen y Lordan 2010) y la dinámica de la flota de arrastre ha demostrado estar relacionada con la biología de algunas de estas especies (Martin et al., 2014; Demestre et al., 2015). Sin embargo, la relación con los descartes es menos conocida y podría ser útil para disminuir las capturas no deseadas tal y como se propone en el capítulo 1 de esta tesis. Un ejemplo útil de esta relación la encontramos en un caladero fangoso del comienzo del talud, donde se descartaron juveniles de cigala y donde observamos un aumento del esfuerzo pesquero coincidiendo con el periodo de reclutamiento de este crustáceo decápodo, que en el Mediterráneo tiene lugar entre el final de la primavera y el inicio del verano (Relini et al., 1998). En este sentido, **el VMS puede ser una herramienta muy recomendable para delimitar periodos prioritarios para la gestión de EFH**.

3. Insuficientes medidas de gestión del descarte de la pesca de arrastre en el Mediterráneo

Una de las principales herramientas de gestión para la pesca en el Mediterráneo, ha sido el establecimiento por parte de la Unión Europea de una talla mínima legal para algunas especies comerciales (en inglés, Minimun Conservation Reference Size, MCRS), fijada en el Anexo III del Reglamento (CE) No 1967/2006. Esta talla es utilizada como referencia para la obligación de desembarque (en inglés, *Landing obligation*, LO), por la que se prohíbe el descarte de todas las especies comerciales con una MCRS asignada, obligando a los pescadores a llevarlas a puerto, sin poder obtener beneficio económico de ello (EU Regulation. 1380/2013). En muchos casos, esta talla de referencia no está bien relacionada con la biología de la especies, ya que está muy lejos de su talla de primera madurez, normalmente representada por la L50, o talla en la que la mitad de los individuos de la población son adultos, y los criterios científicos en los que está basada no están claros (Tsagarakis et al., 2017). Por estos motivos, **una revisión de los criterios sobre los que se basa la MCRS es altamente recomendable**.

La aplicación de la LO puede suponer un trabajo adicional para los pescadores a la hora de tener que triar a bordo y llevar estos individuos, que antes eran descartados al mar, colocados y limpios en cajas hasta puerto. Además, esta nueva tarea podría conllevar una disminución del tiempo efectivo de pesca lo que podría suponer importantes pérdidas económicas. Desde el punto de vista ecológico, las consecuencias esperadas de la implementación de la LO podrían ser positivas, puesto que los pescadores tratarían de evitar ciertas áreas en determinadas épocas donde se capturan juveniles o especies no deseadas sujetas a esta normativa, en aras de mejorar la eficiencia de la pesca (Vilela y Bellido 2015). Sin embargo, la LO deja de lado gran parte de la captura que está compuesta por invertebrados y especies de peces no comerciales, lo cual es insuficiente para la gestión de una pesquería multiespecífica como la pesca de arrastre en el mar Mediterráneo e insuficiente por lo tanto para la conservación de los hábitats. Además, no hay medidas de control reales que puedan hacer cumplirla, pues es poco realista vigilar los procesos de descarte en alta mar, por lo que en la práctica, su cumplimiento es poco factible en el Mediterráneo (Tsagarakis et al., 2017). En este contexto, **se recomienda realizar acciones divulgativas que desemboquen en una mayor concienciación de los pescadores acerca de los beneficios económicos a medio y largo plazo que les supondría evitar la captura de juveniles de especies objetivo.** Ésta podría ser una medida de gestión más útil que la propia obligación de desembarque. Además, **es recomendable la realización de cierres de caladeros, totales, temporales de larga duración o al menos estacionales, en zonas y momentos en los que se detecte gran abundancia de especies con talla inferior a la MCRS. Esto disminuiría las**

cantidades de descarte, protegiendo en gran medida a los hábitats y cumpliendo a la vez con la normativa europea de la LO.

Por otro lado, la LO contempla como exención, entre diferentes posibilidades, a las especies con MCRS que hayan demostrado una alta supervivencia al descarte. Sin embargo, esta exención al igual que la propia LO, deja también de lado una enorme parte de las especies afectadas por el arrastre, que no tienen MCRS, como los invertebrados marinos no comerciales, que suponen gran parte de su descarte (García-de-Vinuesa 2012). La desaparición o disminución en la abundancia o diversidad de estos invertebrados, podría afectar drásticamente a la funcionalidad de los hábitats, disminuyendo en consecuencia los estocs de especies comerciales que dependen directa o indirectamente de estos invertebrados para su alimentación (Lohrer et al., 2004; Demestre et al., 2017; de Juan et al., 2011). A pesar de su importancia para el mantenimiento de los recursos pesqueros, se han llevado a cabo muy pocos estudios hasta el momento para demostrar la supervivencia de estos animales (García-de-Vinuesa 2012; Tsagarakis et al., 2018). Por ese motivo en la sección "a" del capítulo 2 de esta tesis, se abordó esta cuestión, diferenciando además el estudio de la supervivencia del descarte por hábitats e incidiendo especialmente en aquellas especies que forman la base de los hábitats, como el crinoideo *Leptometra phalangium* (Colloca et al., 2004; Massi et al., 2016). Este estudio de supervivencia nos da una idea de la resistencia que tienen las especies de determinados hábitats al descarte por lo que también nos ayuda a conocer la vulnerabilidad que estos hábitats presentan a la pesca de arrastre. Los resultados mostraron una alta supervivencia al descarte de la mayoría de los invertebrados, lo cual nos da una visión optimista para el mantenimiento del buen estado ambiental y la sostenibilidad de los hábitats de fango y de agregación de crinoideos explotados por la pesca de arrastre estudiados en esta tesis (Piet y Hintzen 2012). También encontramos una relación significativa entre tiempo de arrastre y la supervivencia de los invertebrados, y en varias especies se observó que los animales con daños considerables y poca movilidad (nivel de vitalidad) tuvieron mayores índices de mortalidad. Pero hay que tener en cuenta, que la supervivencia de los invertebrados podría verse reducida al ser devueltos a su medio natural por culpa de los daños morfológicos producidos, que podrían conllevar bajas tasas de alimentación o mayor vulnerabilidad a la depredación (Demestre et al., 2000, Bergmann y Moore 2001; Kaiser et al., 2006). Además, hay que tener en cuenta que estos resultados solo son una primera aproximación a la supervivencia de invertebrados descartados en el Mediterráneo, que debe profundizarse con estudios individualizados por especie. Por este motivo en la sección "b" del capítulo 2 de esta tesis y debido a la posibilidad de exención de la LO por tratarse de una especie con MCRS, se llevó a cabo por primera vez en el Mediterráneo un estudio acerca de la supervivencia de la cigala (*Nephrops norvegicus*) al descarte de la pesca de arrastre.

Estudios previos llevados a cabo en el Atlántico han demostrado una alta supervivencia de la cigala al descarte (Mehault et al., 2016; Mérillet et al., 2018). Sin embargo, las distintas condiciones ambientales para la pesca en el Mediterráneo como la profundidad de la pesca, o los acusados cambios estacionales de temperatura tanto del agua del mar como del aire, podrían suponer diferencias significativas en dicha supervivencia. En esta tesis se demostró que existe una fuerte estacionalidad de la supervivencia de las cigalas descartadas, siendo alta en invierno, pero muy baja durante los meses cálidos de verano. Estos resultados pueden ser muy valiosos para la gestión de la pesquería mediterránea de cigala, que con más de 10000 toneladas desembarcadas anualmente, es la cuarta especie de crustáceo más pescada en la región mediterránea (Vasilakopoulos et al., 2016).

A la vista de los resultados de las secciones “a” y “b” del capítulo 2 **se hacen tres recomendaciones:**

i) El cierre estacional de la pesquería de arrastre de la cigala (*Nephrops norvegicus)* durante los meses cálidos, debido a su baja supervivencia (fenómeno que se asocia a la alta temperatura del agua y del aire).

ii) Disminuir el tiempo de arrastre con objeto de reducir los daños físicos en los invertebrados marinos, que de esta manera, al ser devueltos al mar, verían aumentadas su probabilidad de supervivencia.

iii) Implementar medidas técnicas y de manejo de los animales en las barcas, para mejorar su supervivencia al descarte, como: sistemas de triado rápido para devolver al mar los animales con rapidez; mantenimiento de los animales bajo una cubierta húmeda hasta su devolución al mar; la instalación de toldos que ofrezcan zonas de sombra para evitar la exposición de los animales al sol; implementación de grandes recipientes llenos de agua refrigerada para triar la captura mientras está sumergida.

4. Vulnerabilidad a la pesca de arrastre y estado de conservación de comunidades de infauna en hábitats mediterráneos especialmente productivos

Cada hábitat marino tiene unas características físicas propias, que definen las adaptaciones morfológicas y de comportamiento de los organismos que los habitan. Por este motivo las comunidades de animales son específicas en cada tipo de hábitat, poseen rasgos biológicos diferenciados entre sí y pueden responder de diferentes formas ante estresores, ya sean naturales o antropogénicos (Lohrer et al., 2004; Lloret et al., 2007; de Juan and Hewitt 2014; Muntadas et al., 2015). La pesca de arrastre es el mayor estresor conocido hasta el momento para los fondos bentónicos (Sommer 2005), pudiendo provocar una pérdida de funcionalidad de los hábitats a partir de la disminución de especies que realizan funciones esenciales (de Juan et al., 2007; Muntadas et al., 2014). Una de estas funciones es la de servir como base de la cadena trófica de los ecosistemas bentónicos, por lo que la variación en la composición de comunidades bentónicas como las de infauna, puede afectar directa o indirectamente a la alimentación y la condición física de especies comerciales (Lohrer et al., 2004; Lloret et al., 2014). Por este motivo, las comunidades más diversas y abundantes, que tienen mayor nivel de redundancia de rasgos biológicos, muestran una mayor resiliencia al impacto de la pesca de arrastre. Esto quiere decir que son comunidades menos vulnerables, ya que aunque algunas especies tiendan a desaparecer, puede haber otras con rasgos biológicos similares que las sustituyan. De esta manera la funcionalidad del hábitat puede mantenerse estable absorbiendo impactos como el de la pesca de arrastre (de Juan et al., 2007; Muntadas et al., 2014). Sin embargo, hay que tener en cuenta, que este proceso, aunque puede mantener la funcionalidad del ecosistema, supone una pérdida de biodiversidad, ya que las especies más vulnerables al arrastre desaparacen debido a su impacto, lo cual pone en una mala situación a la comunidad a la hora de intentar absorber futuros impactos naturales o antropogénicos, que entonces si podrían suponer una importante pérdida de funcionalidad del hábitat (Muntadas et al., 2016).

Hasta ahora, algunos autores han utilizado los rasgos biológicos de animales marinos para la creación de índices como el enfoque de rasgos biológicos (en inglés, Biological traits approach, BTA) con el objetivo de estudiar los cambios de funcionalidad dentro de los ecosistemas o la vulnerabilidad al arrastre de algunas comunidades (Bremner et al., 2003; Bremner 2008; Muntadas et al 2016; de Juan et al., 2020). Esta tesis ha dado un paso más, al demostrar por primera vez la utilidad del BTA (capítulo 3) para estudiar la vulnerabilidad a la pesca de arrastre de comunidades de infauna de hábitats de maërl y compararla con la vulnerabilidad de comunidades de infauna de hábitats fangosos. Apoyándose en estos resultados, y para ahondar en el conocimiento de la respuesta que comunidades de hábitats concretos presentan ante el impacto de la pesca de arrastre, **se recomienda el uso del BTA como herramienta para poder evaluar y comparar la vulnerabilidad al arrastre y el estado de conservación de comunidades marinas de distintos hábitats**. La comunidad de infauna del hábitat de maërl mostró menor vulnerabilidad al arrastre que la comunidad de infauna del hábitat fangoso. Sin embargo, los cambios en los hábitats podrían no sólo depender de los factores ambientales sino que también hay que tener en cuenta el nivel de esfuerzo pesquero que soporta cada hábitat. Ya que en el capítulo 1, se concluyó que este esfuerzo fue algo menor en el hábitat de maërl que en el fondo de fango. En próximos estudios, para tener una comparativa más clara y evidente entre comunidades explotadas, conviene elegir hábitats con un impacto pesquero muy parecido. Aunque esta selección podría no ser fácil, debido a las propias características de la dinámica pesquera (Martin et al., 2014; Demestre et al., 2015). En cualquier caso, ambos hábitats sufrieron importantes modificaciones de sus comunidades de infauna debido al arrastre por lo que atendiendo a sus características particulares **es recomendable el establecimiento de AMPs en hábitats de maërl y vedas temporales de larga duración en fondos fangosos, ya que podrían contribuir a preservar y recuperar su comunidad de infauna, recuperando su funcionalidad natural, lo que se podría traducir en una mejora de los estocs pesqueros y de sus beneficios económicos, al aumentar la calidad y cantidad de los estocs de especies comerciales disponibles.**

5. Los ácidos grasos como indicadores del impacto de la pesca de arrastre: una herramienta novedosa para la gestión

La composición lipídica de las especies marinas es única y muy valiosa. Única, porque aparecen algunos ácidos grasos esenciales (como los omega 3) que mayoritariamente se dan solamente en especies animales y vegetales marinas, y muy valiosa porque estos ácidos grasos esenciales son necesarios para que los animales, el hombre inclusive, puedan llevar a cabo sus funciones vitales básicas con normalidad (Dalsgaard et al., 2003; Lloret et al., 2007). Los ácidos grasos se generan en gran cantidad en el fitoplancton, por lo que se encuentran altamente disponibles en ecosistemas pelágicos y en los animales que los habitan, como las sardinas o las anchoas (Teodosio et al., 2017; Taipale et al., 2020). Estos nutrientes generados en la zona pelágica, caen por precipitación junto con el resto de materia orgánica hasta el fondo marino, donde algunos animales bentónicos se encargan de fijarlos para su uso a través de la cadena trófica (Sargent et al., 1995a, b; Muntadas et al., 2016). Por este motivo alterar la funcionalidad del ecosistema a partir por ejemplo de la desaparición de filtradores bentónicos, que se sabe que son altamente vulnerables a la pesca de arrastre (de Juan et al., 2007), podría alterar la composición lipídica de las presas o generar escasez de ácidos grasos esenciales como los Omega 3. Teniendo en cuenta la relevancia los ácidos grasos sobre las características del ciclo de vida de los peces, especialmente su reproducción (Lloret et al., 2014), esto supondría poner en peligro la biología y funcionalidad de especies comerciales, afectando así su condición y viabilidad, lo que podría repercutir en la cadena trófica hasta la afectación de grades depredadores y la propia alimentación humana.

El campo de conocimiento de los ácidos grasos ha avanzado en los últimos años, principalmente desde el punto de vista de la alimentación y salud humana, donde por ejemplo se ha evidenciado que el consumo de algunos ácidos grasos como el docosahexaenoico (DHA), tiene beneficios directos sobre la salud de las personas en cuanto a que reduce el riesgo de enfermedades coronarias y ralentiza el deterioro cognitivo (Fard et al., 2019; Chang et al., 2020). También se han utilizado para estudiar las relaciones tróficas en ambientes pelágicos (Teodosio et al., 2017). Sin embargo, rara vez se han utilizado como indicador de perturbación antropogénica o de calidad del hábitat (Levi et al., 2005; Arechavala-Lopez et al., 2019). Por primera vez (capítulo 4), en esta tesis se validó su uso como indicador de la perturbación llevada a cabo por la pesca de arrastre, al igual que como marcador trófico para dos de sus especies objetivos, los salmonetes *Mullus barbatus* y *M. surmuletus*. **Por este motivo se recomienda el uso de los ácidos grasos como indicador del estado de conservación de los hábitats afectados por la pesca de arrastre, y su estudio para determinar relaciones tróficas dentro de ecosistemas bentónicos**. También se encontraron diferencias entre las concentraciones de algunos ácidos grasos como el DHA en salmonetes e infauna procedentes de hábitats de maërl y fangosos, lo que podría suponer una mejor condición para animales que viven en hábitats concretos como los hábitats de maërl. Esto podría llevar a la revalorización de los productos alimenticios de estos hábitats de maërl, que podrían tener mayor valor nutricional, redundando positivamente en la salud humana. También alzaría el valor de estos hábitats como EFHs, puesto que una mayor concentración de ácidos grasos esenciales en los organismos bentónicos de la infauna supondría una mejor calidad de vida de los organismos que los habitan, con un mejor potencial reproductivo, un mejor crecimiento o una menor mortalidad natural (Lloret et al., 2014). Sin embargo, se debe evitar que esta revalorización de productos de ciertos hábitats, sobre todo en el caso de hábitats vulnerables como los fondos de maërl (Basso et al., 2017), supongan un aumento de la presión pesquera llevada a cabo por la flota de arrastre, lo que al final podría suponer una pérdida del propio recurso a explotar. Por lo que **es recomendable, ser especialmente cuidadoso a la hora de gestionar la explotación de los hábitats de maërl, prohibiendo tipologías de pesca dañinas como el arrastre y permitiendo otros tipos de pescas que tengan un impacto mucho menor sobre el bentos como pueden ser los artes de trasmallo o de palangre utilizados por la flota artesanal**.

6. La tragedia de los bienes comunes y la necesidad de avanzar en la divulgación de los resultados científicos para mejorar la gestión de los bienes y servicios ecosistémicos.

Los bienes y servicios que los ecosistemas marinos ofrecen no son de propiedad privada sino que son públicos, por este motivo deberían ser explotados de manera sostenible. Sin embargo, la tragedia de los bienes comunes, descrita ya por Hardin en 1968, nos hace ver que cuando un recurso es público, el usuario no se preocupa de cuidarlo, solo de sacarle el máximo beneficio posible sin tener en cuenta las consecuencias negativas que esto pueda tener para el recurso y en consecuencia para el resto de usuarios. Para que esto no suceda los usuarios deben reconocer el recurso como propio, y una manera de lograrlo es la integración de estos usuarios en la toma de decisiones sobre su gestión (Reed 2008). En este contexto, **al ser los hábitats marinos un bien común de la sociedad, es recomendable que todos los estamentos estén representados en la toma de decisiones acerca de su gestión**. Este tipo de gestión, denominada cogestión, se ha llevado a cabo con éxito en pesquerías artesanales mediterráneas como la del sonso (*Gymnammodytes cicerelus* y *G. semiesquamatus.*). Esta pez óseo, se explota por la flota artesanal con la sonsera a lo largo de varios puntos de la costa catalana, y su gestión involucra a administración, pescadores artesanales, Organizaciones No Gubernamentales (ONGs) y científicos (Lleonart et al., 2014). Sin embargo en lo que respecta a la pesca de arrastre en el Mediterráneo, hoy en día la administración es quién sigue tomando las decisiones sobre la gestión de los recursos. Aunque cada vez existe una mayor cooperación entre entidades pesquera, científicos y administración.

Entre 1961 y 1966 se llevó a cabo el plan experimental sobre la pesca de arrastre en Castellón, que tenía como objetivo procurar una estrategia de gestión pesquera sostenible. En esta experiencia de gestión se tuvo en cuenta a los actores afectados, contando científicos, pescadores y administración (Loastado et al., 1999). Entre otros aspectos, de esta experiencia se aprendió que la base para la resolución de conflictos se encuentra en los propios actores, lo que supone su implicación en la toma de decisiones y en la seriedad de respetar los acuerdos. Tomando el plan Castellón y la más reciente cogestión de la pesquería del sonso como referentes, y a partir de los resultados obtenidos en esta tesis, **se recomienda implantar un plan piloto de cogestión para la flota de arrastre de Blanes en el que se involucrara a pescadores de arrastre, administración, sociedad civil y científicos en la toma de decisiones conjunta, para mejorar la sostenibilidad de esta pesca y avanzar así hacia un equilibrio entre conservación y explotación de sus caladeros**. Algunas de las medidas a discutir entre los actores de este plan piloto, serían el establecimiento de una AMP en el hábitat de maërl, y cierres temporales de larga duración, en los hábitats de agregación de crinoideos.

Además, para que el mensaje científico llegue a los estamentos de toma de decisiones, es fundamental la participación de la sociedad civil, de manera que conozca las problemáticas y pueda influir en la toma de decisiones políticas (Demestre y Masó 2012). Sin embargo, hasta ahora los métodos utilizados para promover la conservación de los ecosistemas marinos no parecen haber tenido resultados realmente positivos en los hábitats afectados por la pesca de arrastre de la cuenca mediterránea. En este sentido, son muy válidas iniciativas con las escuelas como el plan piloto que se desarrolló dentro del proyecto COMSOM. Este proyecto se dedicó a la evaluación del estado de comunidades bentónicas y al estudio de la basura marina como herramienta de gestión del ecosistema, y en él, se hizo partícipe a los alumnos de bachillerato, de un proyecto científico para estudiar de primera mano la basura marina que aparecía en las redes de arrastre (Demestre y Masó 2012). También fue interesante la iniciativa del proyecto divulgativo “100cia” (Generalitat de Catalunya, ACDC-2012), en el que se mostró al público los daños provocados por la pesca de arrastre sobre invertebrados marinos, que fueron expuestos vivos en acuarios. Estas iniciativas pueden ser instrumentos muy útiles para avanzar en la concienciación social de la necesidad de solucionar problemas ambientales actuales**.** La cultura también podría jugar un papel fundamental en la concienciación acerca de los problemas ambientales de la sociedad, a través de canales de amplia difusión como bien podrían ser el cine o la música. Un claro ejemplo del impacto del mundo del cine en la divulgación científica es el documental guionizado por el exvicepresidente estadounidense Al Gore acerca del calentamiento global, “Una verdad incómoda” (2006). Este, el de la mejora de la comunicación de sus resultados, es sin duda es uno de los mayores retos para el mundo científico, si se pretende que nuestro trabajo tenga verdadera influencia en la toma de decisiones.

Conclusiones

1- La caracterización del descarte es una herramienta útil a la hora de localizar ecosistemas bentónicos mediterráneos especialmente productivos como los hábitats de maërl o de agregación de crinoideos.

2- El descarte de la flota arrastrera de Blanes, está compuesto principalmente por individuos de especies comerciales con tallas que se encuentran por debajo de la MCRS, y por especies no deseadas por los pescadores, entre las que encontramos una gran abundancia de invertebrados bentónicos.

3- La dinámica del esfuerzo pesquero de la flota de arrastre de Blanes, tiene en la mayoría de sus caladeros, una componente estacional que está relacionada con la biología de las especies objetivo.

4- El estudio conjunto de los datos VMS, las características de las embarcaciones y el descarte de la pesca de arrastre, constituye una técnica útil para identificar hábitats y momentos prioritarios para la gestión, como periodos de alevinaje en hábitats esenciales para peces. Por este motivo, el sistema de VMS debería ser implantado en toda la flota de arrastre mediterránea, inclusive en las embarcaciones con eslora inferior a 15 metros.

5- La supervivencia de invertebrados bentónicos al descarte de la pesca de arrastre es alta, y está relacionada significativamente con el tiempo de arrastre, por lo que una disminución del tiempo de arrastre tendría efectos positivos en sus posibilidades de supervivencia.

6- La supervivencia de la cigala (*Nephrops norvegicus)* al descarte de la pesca de arrastre en el Mediterráneo noroccidental, depende significativamente tanto del factor estacional como de su estado de vitalidad, siendo mayor durante los meses de invierno y en individuos con altos índices de vitalidad, y menor durante los meses de verano y en individuos con bajos índices de vitalidad.

7- El shock térmico y la prolongada exposición al aire, son factores que se deberían evitar para mejorar la supervivencia de invertebrados marinos afectados por el descarte de la pesca de arrastre. Por lo que la implantación de medidas técnicas y de manejo de animales como sistemas de triado rápido, humidificadores, enfriadores, sistemas de protección contra la radiación solar o que eviten la emersión, podrían ser muy útiles, especialmente durante los meses cálidos.

8- El análisis de rasgos biológicos, es una herramienta útil para estudiar la vulnerabilidad a la pesca de arrastre y el estado de conservación de las comunidades de infauna de hábitats de maërl, puesto que con ella se constató que hábitats de maërl afectados por el arrastre, presentan comunidades de infauna adaptadas, siendo los rasgos biológicos de sus especies menos vulnerables a la pesca de arrastre que los de las especies de comunidades de infauna de habitats de maërl no afectados por dicha pesca.

9- Las diferencias encontradas entre la vulnerabilidad a la pesca de arrastre de comunidades de infauna de hábitats de maërl y de fondos de fango, indica que el estudio de los rasgos biológicos puede ser una técnica útil para comparar la vulnerabilidad al arrastre de comunidades marinas procedentes de diferentes hábitats.

10- El perfil de ácidos grasos de salmonetes e infauna procedentes de hábitats de maërl y fondos fangosos varía en relación a la pesca de arrastre y en función de las características naturales de cada hábitat. Por lo tanto puede ser un instrumento útil para estudiar el estado de conservación y la calidad de hábitats marinos explotados por la pesca de arrastre.

11- Los perfiles de ácidos grasos de salmonetes e infauna mostraron importantes similitudes entre sí, tanto en hábitats de maërl como en fondos fangosos, por lo pueden ser útiles como marcadores para el estudio de relaciones tróficas dentro de ecosistemas bentónicos.

12- El impacto de la pesca de arrastre hace peligrar bienes y servicios de hábitats de maërl como los estocs de especies comerciales que ven variar su base alimenticia y por tanto su condición. El establecimiento de Áreas Marinas Protegidas (AMPs) sobre estos hábitats es necesario para proporcionar una protección efectiva ante dicho impacto, puesto que las figuras de protección actuales no lo consiguen.

13- La alta supervivencia al descarte de invertebrados marinos, como *Leptometra phalangium*, que constituye la base de hábitats de crinoideos, hace pensar que dichos hábitats presentan una vulnerabilidad moderada a la pesca de arrastre. En este hábitat en concreto, la ampliación de las vedas estacionales de la pesca de arrastre que se llevan a cabo en el Mediterráneo noroccidental a vedas temporales de larga duración podría ser herramienta útil para conseguir un equilibrio entre su conservación y explotación.

14- Un trabajo interdisciplinar es necesario para ahondar en la respuesta que hábitats marinos tienen ante impactos antropogénicos o naturales. En este sentido, la integración de parámetros bioquímicos (ácidos grasos), tecnología satelital (VMS) y parámetros biológicos (supervivencia al descarte y BTA), permitió en el transcurso de esta tesis, conocer la vulnerabilidad a la pesca de arrastre y el estado de conservación de hábitats mediterráneos especialmente productivos, y proponer medidas de gestión, direccionadas a mejorar su estado ambiental, y lograr un equilibrio entre conservación y explotación.

15- La degradación de los hábitats de maërl y de agregación de crinoideos, que sigue produciéndose a día de hoy debido al impacto continuado de la pesca de arrastre en el noroeste del mar Mediterráneo, precisa de medidas de gestión que deben ser tomadas de manera urgente por la administración, para evitar la irreversible pérdida de los bienes y servicios que proporcionan estos hábitats.

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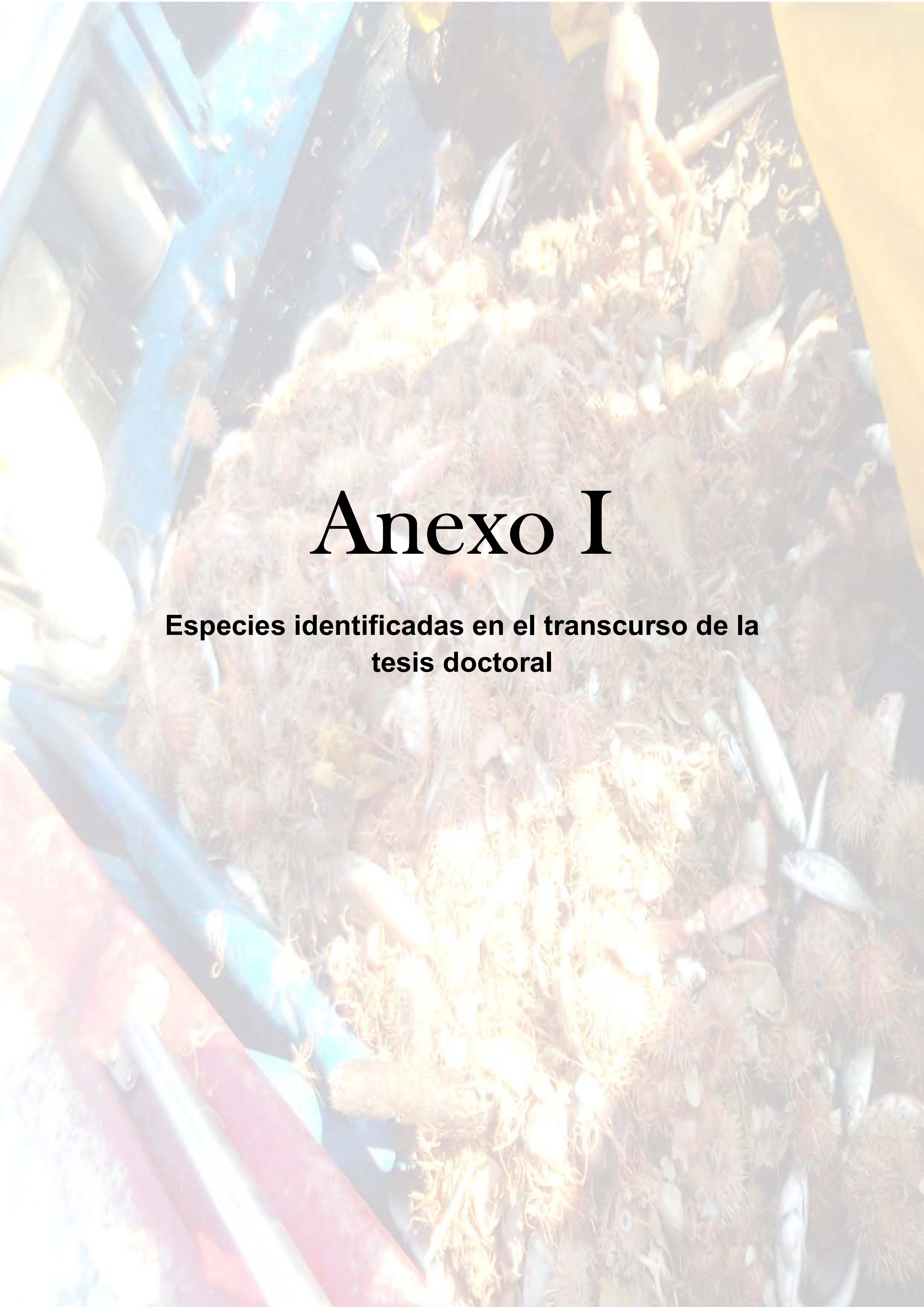


Anexo I

Especies identificadas en el transcurso de la tesis doctoral

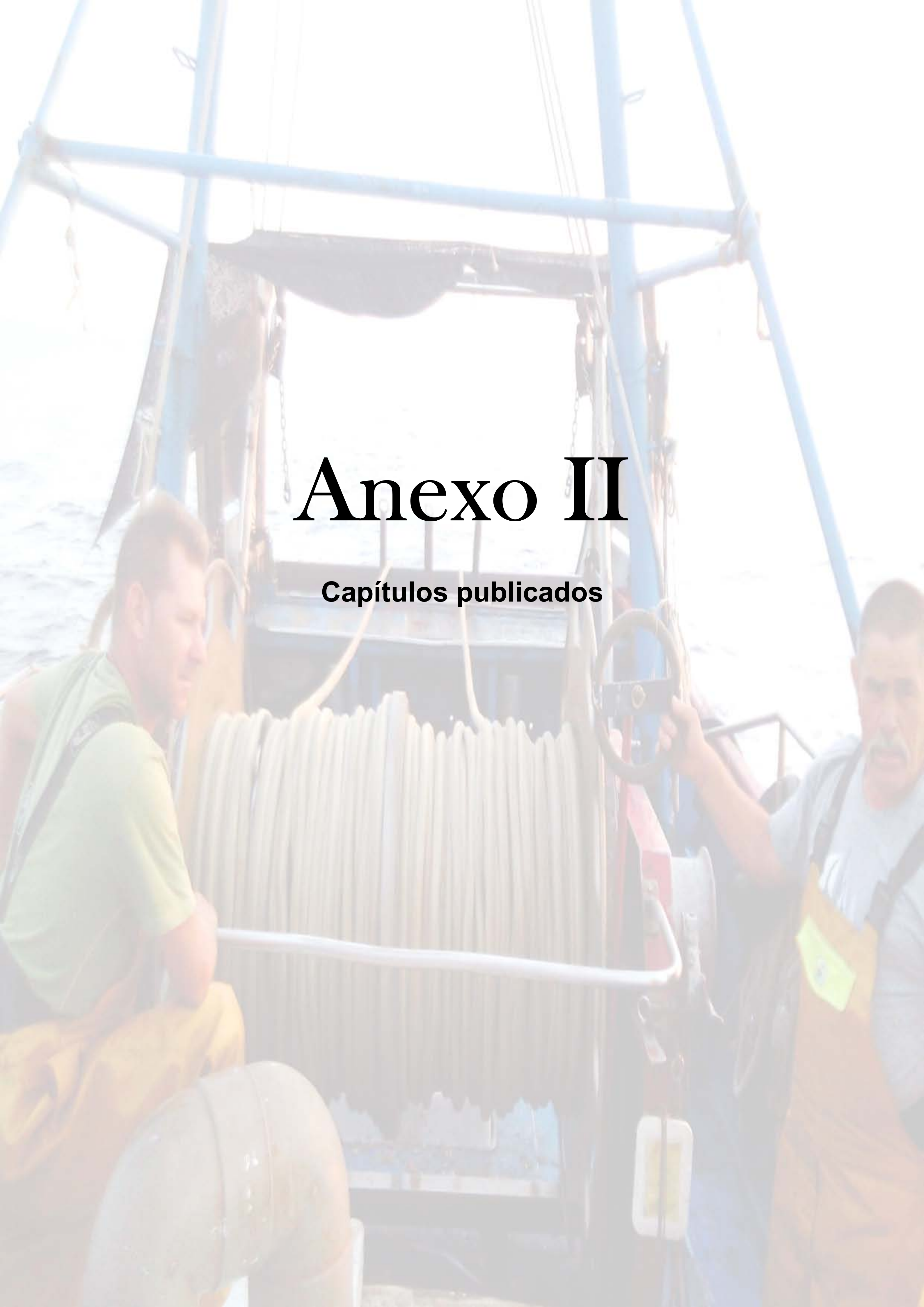
Anexo 1: Listado de especies identificadas a lo largo de la tesis.

Especie	Fracción	Filo
Abralia veranyi	Descarte	Mollusca
Alcyonium palmatum	Descarte	Cnidaria
Alloteuthis media	Comercial	Mollusca
Allotheuthis sublata	Descarte	Mollusca
Alpheus glaber	Descarte	Arthropoda
Ampharetidae	Infauna	Annelida
Amphipoda	Infauna	Arthropoda
Anseropoda placenta	Descarte	Echinodermata
Antedon mediterranea	Descarte	Echinodermata
Aphrodita aculeata	Descarte	Annelida
Argentina sphyraena	Descarte	Chordata
Aristeus antennatus	Comercial	Arthropoda
Aristeus antennatus	Descarte	Arthropoda
Arnoglossus laterna	Descarte	Chordata
Arnoglossus ruepelli	Descarte	Chordata
Arnoglossus sp.	Comercial	Chordata
Arnoglossus tori	Descarte	Chordata
Ascidia mentula	Descarte	Chordata
Ascidiacea	Infauna	Chordata
Asteroidea	Infauna	Echinodermata
Astropartus mediterraneus	Descarte	Echinodermata
Astropecten aranciacus	Descarte	Echinodermata
Astropecten irregularis	Descarte	Echinodermata
Axinella polypoides	Descarte	Porifera
Bathypolypus sponsalis	Descarte	Chordata
Bivalvia	Infauna	Mollusca
Blennius ocellaris	Descarte	Chordata
Boops boops	Comercial	Chordata
Brissopsis liryfera	Descarte	Echinodermata
Calliactis parasitica	Descarte	Cnidaria
Callionymus maculatus	Descarte	Chordata
Calliostoma granulatum	Descarte	Mollusca
Capitellidae	Infauna	Annelida
Capros aper	Descarte	Chordata
Carapus acus	Descarte	Chordata
Cassuridae	Infauna	Annelida
Chaetaster longipes	Descarte	Echinodermata
Chauliodus sloani	Descarte	Chordata
Chelidonichthys cuculus	Descarte	Chordata
Chelidonichthys lucerna	Descarte	Chordata
Chelidonichthys obscurus	Descarte	Chordata
Chimaera monstrosa	Descarte	Chordata
Chlamys opercularis	Descarte	Mollusca
Chlorotocus crassicornis	Descarte	Arthropoda
Chrysaora hysoscella	Descarte	Cnidaria

Especie	Fracción	Filo
Cidaris cidaris	Descarte	Echinodermata
Cirratulidae	Infauna	Annelida
Citharus linguatula	Comercial	Chordata
Citharus linguatula	Descarte	Chordata
Cladocera	Infauna	Arthropoda
Coelorhynchus coelorhynchus	Descarte	Chordata
Conger conger	Comercial	Chordata
Conger conger	Descarte	Chordata
Copepoda	Infauna	Arthropoda
Crinoidea	Infauna	Echinodermata
Cumacea	Infauna	Arthropoda
Dardanus arrosor	Comercial	Arthropoda
Dardanus arrosor	Descarte	Arthropoda
Decapodos	Infauna	Arthropoda
Denteltosteus quadrimaculatus	Descarte	Chordata
Diazona violácea	Descarte	Chordata
Diogenes pugilator	Descarte	Arthropoda
Diplecogaster bimaculata	Descarte	Chordata
Diplodus annularis	Comercial	Chordata
Dorvilleidae	Infauna	Annelida
Echinaster sepositus	Descarte	Echinodermata
Echinus melo	Descarte	Echinodermata
Eledone cirrhosa	Comercial	Mollusca
Eledone cirrhosa	Descarte	Mollusca
Epigonus constanciae	Descarte	Chordata
Epigonus telescopus	Descarte	Chordata
Equinoidea	Infauna	Echinodermata
Escafòpoda	Infauna	Mollusca
Etmopterus spinax	Descarte	Chordata
Eunicella sp	Descarte	Cnidaria
Eunicidae	Infauna	Annelida
Eutrigla gurnardus	Descarte	Chordata
Evalia tuberosa	Descarte	Arthropoda
Flabigeridae	Infauna	Annelida
Funiculina quadrangularis	Descarte	Cnidaria
Gadiculus argenteus	Descarte	Chordata
Galeus melastomus	Descarte	Chordata
Gasteròpodes	Infauna	Mollusca
Gliceridae	Infauna	Annelida
Goneplax romboides	Descarte	Arthropoda
Gracilechinus acutus	Descarte	Echinodermata
Helicolenus dactylopterus	Comercial	Chordata
Helicolenus dactylopterus	Descarte	Chordata
Hesionidae	Infauna	Annelida
Histioteuthis reversa	Descarte	Mollusca

Especie	Fracción	Filo
Holothuria forskali	Descarte	Echinodermata
Holoturoidea	Infauna	Echinodermata
Illex condetii	Comercial	Mollusca
Illex condetii	Descarte	Mollusca
Inachus comunisimus	Descarte	Arthropoda
Inachus phalangium	Descarte	Arthropoda
Isopoda	Infauna	Arthropoda
Lampanictus crocodrilus	Descarte	Chordata
Lepidopus caudatus	Descarte	Chordata
Lepidorhombus boscii	Comercial	Chordata
Lepidotrigla cavillone	Descarte	Chordata
Leptometra phalangium	Descarte	Echinodermata
Liocarcinus depurator	Comercial	Arthropoda
Liocarcinus depurator	Descarte	Arthropoda
Loligo vulgaris	Comercial	Mollusca
Loligo vulgaris	Descarte	Mollusca
Lophius budegassa	Comercial	Chordata
Lophius piscatorius	Comercial	Chordata
Lophius budegassa	Descarte	Chordata
Lophius piscatorius	Descarte	Chordata
Luidia ciliaris	Descarte	Echinodermata
Lumbrineridae	Infauna	Annelida
Lunatia fusca	Descarte	Mollusca
Lytocarpia myriophyllum	Descarte	Cnidaria
Macropipus tuberculatus	Comercial	Arthropoda
Macropipus tuberculatus	Descarte	Arthropoda
Macropodia longipes	Descarte	Arthropoda
Macropodia longirostris	Descarte	Arthropoda
Macroramphosus scolopax	Descarte	Chordata
Magelonidae	Infauna	Annelida
Maldanidae	Infauna	Annelida
Marthasterias glacialis	Descarte	Echinodermata
Medorippe lanata	Descarte	Arthropoda
Merluccius merluccius	Comercial	Chordata
Microcosmus sulcatus	Descarte	Chordata
Micromesistius potassou	Comercial	Chordata
Molva dypterygia	Comercial	Chordata
Molva dypterygia	Descarte	Chordata
Molva molva	Descarte	Chordata
Monodaeus couchii	Descarte	Arthropoda
Mullus barbatus	Comercial	Chordata
Mullus surmulletus	Comercial	Chordata
Munida intermedia	Descarte	Arthropoda
Munida iris	Descarte	Arthropoda
Munida rutllanti	Descarte	Arthropoda
Munida sp.	Comercial	Arthropoda
Myctophum sp.	Descarte	Chordata
Nematoda	Infauna	Nematoda
Nemertesia ramosa	Descarte	Cnidaria
Nemertea	Infauna	Nemertea
Nemichthys scolopaceus	Descarte	Chordata
Nephrops norvegicus	Comercial	Arthropoda
Nephrops norvegicus	Descarte	Arthropoda
Nereidae	Infauna	Annelida
Notacanthus bonaparte	Descarte	Chordata
Notolepsis rissoi	Descarte	Mollusca
Octopus salutii	Descarte	Mollusca
Octopus vulgaris	Comercial	Mollusca
Ofiuroidea	Infauna	Echinodermata
Onuphidae	Descarte	Annelida
Onuphidae	Infauna	Annelida
Ophiacantha setosa	Descarte	Echinodermata
Ophiocomina nigra	Descarte	Echinodermata
Ophiotrix fragilis	Descarte	Echinodermata
Ophisurus serpens	Descarte	Chordata
Ophiura texturata	Descarte	Echinodermata
Orbinidae	Infauna	Annelida
Ostracoda	Infauna	Arthropoda
Ostrea edulis	Descarte	Mollusca
Pagellus bogaraveo	Comercial	Chordata
Pagellus erythrinus	Comercial	Chordata
Pagurus alatus	Descarte	Arthropoda
Pagurus excavatus	Descarte	Arthropoda
Pagurus prideauxi	Descarte	Arthropoda
Paraonidae	Infauna	Polychaeta
Parapenaeus longirostris	Comercial	Arthropoda
Parapenaeus longirostris	Descarte	Arthropoda
Parastichopus regalis	Comercial	Echinodermata
Parastichopus regalis	Descarte	Echinodermata
Partenope macrochelos	Descarte	Arthropoda
Pasiphaea multidentata	Descarte	Arthropoda
Pectinaridae	Infauna	Annelida
Peltaster placenta	Descarte	Echinodermata
Pennatula phosphorea	Descarte	Cnidaria
Pennatula rubra	Descarte	Cnidaria
Phasiphaea sivado	Descarte	Arthropoda
Phasiphaea sivadi	Comercial	Arthropoda
Phycis blennoides	Comercial	Chordata
Phycis blennoides	Descarte	Chordata
Phyllodocidae	Infauna	Annelida
Picnogonida	Infauna	Arthropoda
Pinna nobilis	Descarte	Mollusca
Pirosoma atlanticum	Descarte	Chordata
Pisa nodipes	Descarte	Arthropoda

Especie	Fracción	Filo
Plesionika acanthonotus	Descarte	Arthropoda
Plesionika giglioli	Descarte	Arthropoda
Plesionika heterocarpus	Descarte	Arthropoda
Plesionika martia	Descarte	Arthropoda
Poliplacofora	Infauna	Mollusca
Polyonidae	Infauna	Annelida
Pontocaris lacazei	Descarte	Arthropoda
Pteria hirundo	Descarte	Mollusca
Pteroctopus tetracirrhus	Descarte	Mollusca
Pteroides spinosum	Descarte	Cnidaria
Raja asterias	Descarte	Chordata
Raja clavata	Descarte	Chordata
Raja miraletus	Descarte	Chordata
Raja sp.	Comercial	Chordata
Rossia macrosoma	Descarte	Mollusca
Sardinela aurita	Descarte	Chordata
Scomber scombrus	Comercial	Chordata
Scorpaena notata	Descarte	Chordata
Scorpaena scropha	Descarte	Chordata
Scorpaena sp.	Comercial	Chordata
Scyliorhinus canicula	Comercial	Chordata
Scyliorhinus canicula	Descarte	Chordata
Sepia elegans	Descarte	Mollusca
Sepia officinalis	Comercial	Mollusca
Sepia orbignyana	Comercial	Mollusca
Sepia orbignyana	Descarte	Mollusca
Sepietta oweniana	Descarte	Mollusca
Seranus cabrilla	Comercial	Chordata
Sergia robusta	Descarte	Arthropoda
Serranus cabrilla	Descarte	Chordata
Serranus hepatus	Descarte	Chordata
Sertularella gayi	Descarte	Cnidaria
Sipunculida	Infauna	Annelida
Solenocera membranácea	Descarte	Arthropoda
Spatangus purpureus	Descarte	Echinodermata
Spicara flexuosa	Descarte	Chordata
Spicara smaris	Descarte	Chordata
Spinolambrus macrochelos	Descarte	Arthropoda
Spionidae	Infauna	Annelida
Spondyliosoma cantharus	Comercial	Chordata
Stomias boa boa	Descarte	Chordata
Suberites sp.	Descarte	Porifera
Syllidae	Infauna	Annelida
Symphurus nigrescens	Comercial	Chordata
Synchiropus phaeton	Descarte	Chordata
Tanaidacea	Infauna	Arthropoda
Terebellidae	Infauna	Polychaeta
Tethyaster subinermis	Descarte	Echinodermata
Todarodes sagittatus	Comercial	Mollusca
Torpedo marmorata	Descarte	Chordata
Trachinus draco	Comercial	Chordata
Trachurus picturatus	Comercial	Chordata
Trachurus trachurus	Comercial	Chordata
Trachythyone elongata	Descarte	Echinodermata
Trigla lyra	Descarte	Chordata
Trigla lyra	Comercial	Chordata
Trigloporus lastoviza	Descarte	Chordata
Trisopterus capellanus	Comercial	Chordata
Uranoscopus scaber	Comercial	Chordata
Zeus faber	Comercial	Chordata



Anexo II

Capítulos publicados

Discards regulation vs Mediterranean fisheries sustainability
M. Demestre and F. Maynou (eds)

Scientia Marina 82S1
December 2018, 165-174, Barcelona (Spain)
ISSN-L: 0214-8358
https://doi.org/10.3989/scimar.04755.17A

Linking trawl fleet dynamics and the spatial distribution of exploited species can help to avoid unwanted catches: the case of the NW Mediterranean fishing grounds

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Summary: With the full implementation of the landing obligation on 1 January 2019, In European waters it will become mandatory for the trawling fleet to land at port all catches of certain species because, according to Article 15 of the new European Common Fisheries Policy, the species subject to the minimum conservation reference size (MCRS) cannot be discarded. Additionally, since 2005, trawlers over 15 m in length are required to carry an onboard vessel monitoring system (VMS), which generates information on fleet dynamics. The objective of this work was to provide a tool for avoiding unwanted catches by integrating the catch study of trawlers operating in the port of Blanes together with VMS data. To achieve this objective, the catches of 40 hauls were monitored, sampled and analysed together with VMS data for the years 2012-2014 integrated in a geographical information system. The results show that specimens below the MCRS were often captured in crinoid aggregation habitats, bottoms with maërl and muddy bottoms that were identified as nursery habitats of commercial species, e.g. *Merluccius merluccius*, *Pagellus* spp. and *Mullus* spp. VMS data showed considerable fishing pressure on areas with maërl and muddy habitats during the recruitment periods of these and other commercially relevant species. Implementing spatial or seasonal closures in habitats where species regulated by the MCRS are subject to catches could be a useful tool for preventing unwanted catches.

Keywords: unwanted catches; northwestern Mediterranean; trawl fishery; discard; VMS; MCRS.

Vincular la dinámica de la flota de arrastre y la distribución espacial de las especies explotadas puede ayudar a evitar capturas no deseadas: el caso de los caladeros del Mediterráneo noroccidental

Resumen: Con la plena aplicación de la Obligación de desembarque a partir del 1 de enero de 2019, pasará a ser obligatorio para la flota de arrastre desembarcar en puerto todas las capturas de ciertas especies, que según el Artículo 15 de la nueva política pesquera común no pueden ser descartadas, ya que están sujetas a MCRS. Por otro lado, desde 2005, se requiere a los arrastreros de más de 15 m de longitud, llevar a bordo un VMS, que proporciona información acerca de la dinámica de la flota. El objetivo de este trabajo fue proporcionar una herramienta para evitar capturas no deseadas integrando el estudio de la captura de arrastreros que operan en el puerto de Blanes junto con datos VMS de la flota de arrastre. Para lograr dicho objetivo, las capturas de 40 lances fueron monitoreadas, muestreadas y analizadas junto con los datos VMS de los años 2012-2014 integrados en un Sistema de Información Geográfica. Los resultados muestran que se capturaron de forma notable especímenes por debajo de la MCRS en hábitats de agregación de crinoideos, fondos con presencia de maërl y fondos fangosos que fueron identificaron como hábitats de cría para especies como *Merluccius merluccius*, *Pagellus* spp. y *Mullus* spp. Los datos VMS mostraron una notable presión pesquera en hábitats fangosos y fondos con presencia de maërl durante los períodos de reclutamiento de estas y otras especies comerciales relevantes. El uso de cierres espaciales o temporales en hábitats sujetos a descarte de especies reguladas por MCRS podría ser una herramienta útil para evitar capturas no deseadas.

Palabras clave: capturas no deseadas; Mediterráneo noroccidental; pesca de arrastre; descarte; VMS; MCRS.

Citation/Cómo citar este artículo: Garcia-de-Vinuesa A., Sola I., Quattrocchi F., Maynou F., Demestre M. 2018. Linking trawl fleet dynamics and the spatial distribution of exploited species can help to avoid unwanted catches: the case of the NW Mediterranean fishing grounds. Sci. Mar. 82S1: 165-174. https://doi.org/10.3989/scimar.04755.17A

Editor: C. Viva.

Received: January 25, 2018. **Accepted:** September 19, 2018. **Published:** October 30, 2018.

INTRODUCTION

The European Commission defines discarding as the practice of returning unwanted catches to the sea, dead or alive, because they are too small, the fisherman has no quota, or certain catch composition rules apply. This practice has been recognized globally among the most important issues for fisheries management because it is considered a source of uncertainty in the assessment of commercial stocks and negatively affects biodiversity and community structure (Bellido et al. 2011, Tsagarakis et al. 2014).

The sustainable exploitation of marine ecosystems and their natural resources is one of the fundamental goals of the strategy of the European Union (EU) in the framework of research and development (Horizon 2020). For this purpose, the new Common Fishery Policy aims to reduce or avoid unwanted catches as much as possible and, if necessary, to maximize their utilization (non-human consumption) without creating a market for species with an MCRS (EU Reg. 1380/2013). It therefore aims to gradually eliminate discards from community waters.

The reasons for discarding are many and varied and can be driven by economic, sociological, environmental or biological factors (Damalas et al. 2015). In the Mediterranean, total discards have been estimated at 18.6% of the total catch (Tsagarakis et al. 2014). However, bottom trawling is one of the least selective fishing methods (Sommer 2005) and the one with the largest discard of biomass production, accounting for an average of 32.9% of the total catch (Tsagarakis et al. 2014). This discard is less pronounced (<20%) in deep water trawl fisheries, where exploitation targets a single resource, *Aristeus antennatus*, which is exploited between 405 and 773 m (Sanchez et al. 2004). For this reason, in our work, red shrimp fishing grounds were not considered due to the low discard amount in this depth zone in comparison with other shallower fishing grounds and because this discard is mainly composed of non-commercial species (Gorelli et al. 2016) that do not fall under the landing obligation (Article 15 of EU Reg. 1380/2013)**.** On the other hand, previous studies in the Catalan Sea at upper slope depths (between 200 and 400 m) showed that *Nephrops norvegicus* trawl fishery discard rates can be considerable, and species with high commercial value, such as *N. norvegicus* and *Parapenaeus longirostris*, are discarded (Garcia-de-Vinuesa 2012). Lastly, trawl fisheries on the continental shelf typically target several species, such as the high-value *Stichopus regalis*, *Mullus* spp., *Loligo vulgaris*, *Merluccius merluccius* and *Lophius* spp. between 50 and 200 m, where the discarded percentage of the catch may be approximately 60% or higher (Durell et al. 2008, Sanchez et al. 2004, Carbonell et al. 2003).

The capture of juveniles is one of the main reasons for discarding in the Mediterranean Sea (Bellido et al. 2017), and some vulnerable and highly productive Mediterranean zones (such as maërl beds or crinoid aggregations located on the continental shelf and slope) function as nursery areas and are negatively affected by this type of discard (Colloca et al. 2004, Barberá et al. 2003, Hall-Spencer et al. 2003). Maërl beds have been studied for decades, and they are particularly susceptible to physical disturbance (De Juan et al. 2013); although they are protected in Annex I of the Habitat Directive (EU Dir. 92/43/EEC), fishing pressure is still exerted on them (Demestre et al. 2017). However, crinoid aggregation ecosystems have been less studied (Colloca et al. 2004, Reale et al. 2005, Mangano et al. 2010), and unfortunately have no specific legal protection. Many of the commercial species habitually discarded by trawling operations in these ecosystems will soon be affected by the new European landing obligation.

In the European waters of the Mediterranean Sea**,** the management of bottom trawling is carried out mainly through fishing effort controls, which may not be an effective system for discard management (Damalas et al. 2015). Trawl fishing is prohibited at less than 50 m depth, more than 1000 m depth and less than 1.5 nautical miles of the coast (EU Reg. 1967/2006); other restrictions include marine protected areas and temporal closures, which, in the case of the Spanish Mediterranean trawl fleet, are usually applied for one or two months per year. Technical measures include an MCRS for the main target species under Article 15 of EU Reg. 1380/2013, which specifies that animals below their MCRS should be landed at port. In addition, size regulations for nets are in place, specifying that 40 mm square-mesh net or 50 mm diamond-mesh net must be used for the cod-end (EU Reg. 1967/2006). In the Spanish Mediterranean control of the fleet, the number of hours and days at sea is limited, and since 2005, in European waters fishing vessels exceeding 15 m overall length must be equipped with a satellite-based vehicle monitoring system (VMS) (EU Reg. 404/2011) that, at least every two hours, provides data to the fisheries control authorities on the location, course and speed of vessels. This is one of the latest systems for controlling fishing effort adopted by European fleets operating in the Mediterranean Sea, where VMS has been proven to provide reliable information on habitat impacts (Hinz et al. 2013).

VMS together with other technical vessel data can be used to determine fishery fleet effort and its spatial and seasonal dynamics, which help identify the priority areas/seasons for management (Martín et al. 2014, Demestre et al. 2015). This knowledge, along with catch data, can be used to identify especially vulnerable or productive habitats in order to propose seasonal bans or enforce no-take areas to avoid unwanted catches below the MCRS.

Species covered under European legislation in the Mediterranean (Annex III of EU Reg. 1967/2006) include 20 fish, 4 crustaceans and 3 mollusc bivalves that are affected by MCRS. In addition, local level fishery control measures can often be more restrictive. Particularly in Catalonia, when taking into account European, national and local regulations, the number of species affected by size and/or weight regulations includes 34 fish, 5 crustaceans, 6 bivalves, 1 gastropod, 1 cnidarian, 3 echinoderms and 1 cephalopod (Generalitat de Catalunya 2015). Species only affected by local regulations are not subject to landing obligations, but

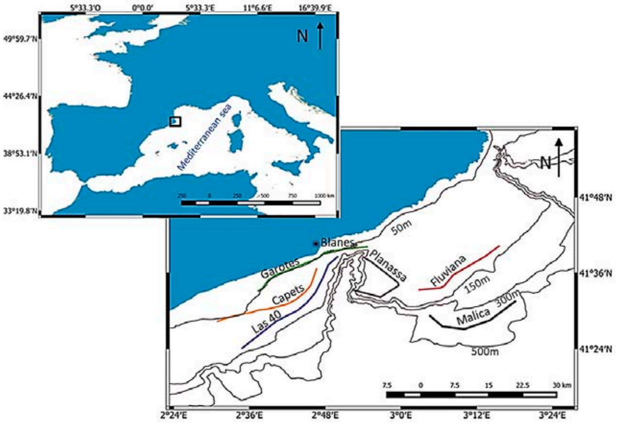

Fig. 1. – Study area indicating the six studied fishing grounds adjacent to Blanes port (northwestern Mediterranean).

when they are below the legal size or weight, they must be discarded and cannot be kept on board. Different regulations for a large number of species from the same fishery could involve an operational problem for fishing activities.

Considering the importance of the new European discard regulation, this work proposes to link VMS with discard catch data, paying special attention to the species regulated by MCRS, and at the local level for a representative trawling fleet from the port of Blanes, Catalonia (NW Mediterranean), in order to propose management measures that avoid or minimize unwanted catches.

MATERIALS AND METHODS

Study area

The study area is located in the northwest Mediterranean Sea, comprising five fishing grounds located in the vicinity of a submarine canyon that is frequented by the trawl fleet from the port of Blanes (Fig. 1).

Four of the fishing grounds chosen for the study are on the continental shelf, normally in the depth range of 54 to 145 m (Table 1). Uniquely, at Planassa, the depth reaches 530 m, as this fishing ground includes the northeastern edge of the Blanes canyon. The fifth fishing ground is located on the upper slope, between 196 and 494 m depth.

Data source

Between March 2016 and February 2017, sampling was carried out on four commercial trawlers in areas where discard activities were common. Generally, two field trips per month were carried out, one on the continental shelf where three vessels worked, and one on the upper slope where one vessel worked. It was attempted to completely cover the possible spatiotemporal variability at the fishing grounds worked by the Blanes trawl fleet, with the exception of the deepest fishing ground where *Aristeus antennatus* was the target species. Between 1 and 3 hauls were carried out on each fishing trip. In total, 40 hauls were analysed on board, from which biomass and abundance of commercial catch by species were recorded along with the biomass of regulated and unregulated discard.

From 23 hauls, between 7 and 10 kg of the discard fractions were randomly selected and transported to the laboratory, where the organisms were classified to the lowest possible taxonomic level. Abundance and biomass of each species were obtained, and the individuals regulated by MCRS or local regulations were measured.

During the fishing trips, effective trawl time, initial and final position and speed during trawl (2.4-3.2 knots) were recorded. Technical vessel data such as gross tonnage (GT) and overall length were also recorded. Finally, distance between trawl wings was provided by previous measurements carried out by fishermen.

VMS data of the Blanes port trawl fleet for the years 2012, 2013 and 2014 were provided by the *Ministerio de Agricultura, Pesca y Medio Ambiente* (MAGRAMA) (Spanish Ministry of Agriculture, Fisheries and Environment).

Data analysis

Biomass (B) and abundance (AB) of discards by species were extrapolated to the total fraction of discards with the following formula:

$$\text{Species AB or B} = $$
$$= \frac{\text{AB or B (species sampled)} \times \text{AB or B (total discard)}}{\text{AB or B (discard sampled)}}$$

Discard and commercial species abundance and biomass were then standardized to hectares using technical vessel, cruise and catch data as follows:

$$\text{Species AB or B standardized} =$$
$$= \frac{\text{AB or B (species sampled)}}{\text{speed}\ \frac{\text{m}}{\text{s}} \times \text{SBW(m)} \times \text{HD(s)}} \times 10000$$

where SBW is the mean distance between trawl wings and HD is the haul duration.

With the Primer 6.1.2 statistical program (Clarke and Gorley 2006), discard abundance by species and hauls were square-root transformed, and their Bray-Curtis similarity matrix was calculated. From this similarity matrix, a multidimensional scaling (MDS) plot was generated to visualize the ordination pattern between discards of the 23 hauls analysed.

Table 1. – Fishing grounds depth characteristics.

Fishing grounds depth characteristics	Capets	Fluviana	Las 40	Garotes	Malica	Planassa
Depth min (m)	70	93	83	54	195	85
Depth max (m)	113	144	102	107	493	530
Depth range (m)	42	51	19	52	298	444

Table 2. – Average (Av) biomass of catch fractions for each fishing ground studied.

Catch fractions (kg ha^{-1})	Capets	Fluviana	Las 40	Garotes	Malica	Planassa
Av. total catch	3.93	7.44	6.66	7.53	2.66	8.22
Av. commercial catch	1.27	1.42	1.79	1.68	1.97	1.83
Av. Regulated discard	0.36	0.13	0.51	3.54	0.14	0.30
Av. Unregulated discard	2.31	5.90	4.37	2.31	0.56	6.09
Av. Total discard	2.66	6.02	4.88	5.85	0.69	6.39

Table 3. – SIMPER discard analysis taking fishing ground as a factor, showing average similarity between hauls (Av. similarity) and with respect to species, average abundance in individuals per hectare (Av.Ab), average similarity contribution (Av.Sim), average similarity divided by standard deviation (Av.Sim/SD), similarity contribution in percentage (C) and accumulated similarity contribution in percentage (Cum) to the five species with the greatest contribution to similarity in each fishing ground.

	Av.Ab (ind. ha^{-1})	Av.Sim	Av.Sim/SD	C %	Cum %
Las 40-Capets Av. similarity: 39.54					
Ophiura texturata	4.02	6.11	2.45	15.46	15.46
Spicara smaris	1.52	2.8	4.5	7.08	22.54
Echinaster sepositus	1.29	2.07	4.27	5.24	27.78
Echinus melo	1.2	1.93	2.83	4.88	32.66
Boops boops	1.49	1.72	2.84	4.35	37.01
Planassa Av. similarity: 26.65					
Leptometra phalangium	19.1	5.77	1.15	21.65	21.65
Gracilechinus acutus	2.75	2.31	0.88	8.66	30.31
Capros aper	3.71	1.62	0.9	6.09	36.4
Echinus melo	2.61	1.32	0.89	4.95	41.35
Plesionika heterocarpus	3.39	1.15	0.41	4.31	45.67
Fluviana Av. similarity: 15.82					
Leptometra phalangium	45.39	6.54	0.83	40.07	40.07
Scyliorhinus canicula	2.71	1.97	2.55	12.43	52.5
Echinus melo	4.63	1.92	1.59	12.15	64.65
Spicara smaris	1.26	0.96	1.59	6.08	70.73
Calliactis parasitica	1.04	0.72	0.58	4.55	75.29
Malica Av. similarity: 57.90					
Nephrops norvegicus	1.93	8.29	3.32	14.33	14.33
Scyliorhinus canicula	1.62	6.63	1.57	11.46	25.78
Phycis blennoides	1.15	5.81	4.59	10.04	35.82
Arnoglossus rueppelli	0.99	4.65	5.44	8.03	43.85
Trigla lyra	1.16	3.72	1.56	6.43	50.28
Garotes Av. similarity: 33.11					
Boops boops	6.54	24.01	-	72.52	72.52
Pagellus erythrinus	1.21	3.7	-	11.17	83.69
Echinaster sepositus	0.56	2.14	-	6.45	90.14
Mullus barbatus	0.36	1.31	-	3.95	94.1
Spicara smaris	3.35	1.24	-	3.74	97.84

After MDS, similarity percentage (SIMPER) analysis was carried out with the non-transformed matrix to determine the relative contribution that discard species made to the similarity among hauls using fishing ground as a factor. Due to the protection figure of maërl, a deeper analysis was carried on one fishing ground with maërl presence, where the average abundance of hauls by species was calculated.

The seasonal size distribution of the regulated discard species was represented graphically with the R 3.4.3 statistical program (R Core Team 2017) to summarize it both temporally and spatially.

VMS together with GT data of 28 trawlers from Blanes active between 2012 and 2014 were used to estimate the spatial and seasonal distribution of fishing effort. The information from VMS data does not indicate whether a vessel is fishing, so a speed filter was applied to raw data taking into account only VMS positions with trawl speeds of less than 4 knots (Demestre et al 2015, Martín et al 2014). Duplicated positions were deleted, and then filtered and unduplicated VMS data sets were used to represent the fishing effort distribution on a grid with a cell size of 1 km^2, which offers a good resolution for the spatial characteristics of this fishery.

The fishing effort in each cell was estimated as follows:

$$\text{Fishing effort} = \sum_i \text{NVMS}_i \times \text{GT}_i$$

where NVMS_i is the number of VMS points of each vessel per cell in a specific month and GT_i is the GT value of each vessel. Both filtering and estimation were performed using the software QGIS 2.10.0 (QGIS 2015).

Finally, to study the most relevant links between fishing effort and regulated discards, the abundance and biomass of species with MCRS was calculated at particular fishing grounds and months and VMS data was plotted for these months and fishing grounds.

RESULTS

Catch characterization

A total of 45 species were found in the commercial catch, and 15 regulated species and 171 non-regulated

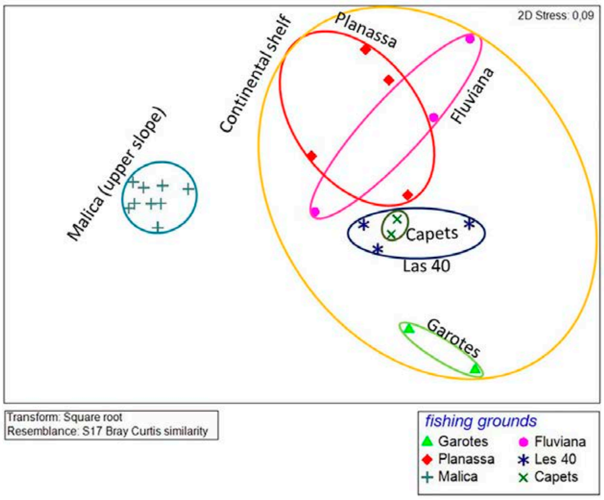

Fig. 2. – Discard MDS analysis; hauls and their occupied space are shown by fishing ground.

species were found in the discards. Table 2 shows the average biomass for each catch fraction from the fishing grounds studied.

Total discard characterization

The MDS discard analysis shows a clear difference between continental shelf and upper slope hauls. Garotes and Malica were separated from the other fishing grounds (Fig. 2). On the other hand, Planassa and Fluviana shared some space, and Capets was within the area occupied by Las 40. Due to the spatial overlap and the strong connection between Capets and Las 40 in the MDS analysis, it was decided to jointly analyse these two fishing grounds for the rest of the work.

In the SIMPER discard analysis, *Echinus melo* had an important presence in Las 40-Capets, Planassa and Fluviana, contributing 12.15% of the similarity among Fluviana samples (Table 3). A noteworthy finding was that *Leptometra phalangium* explained more than 40% of the similarity at Fluviana and more than 20% of the similarity at Planassa.

Boops boops explained more than 70% of the similarity at Garotes, where commercial species such as *Mullus barbatus* or *Pagellus erythrinus* were always discarded as well. Finally, *Nephrops norvegicus* was the discarded species with the highest percentage of similarity to Malica (14.33%).

Table 4. – Species abundance in Garotes hauls and their average (Av. Garotes), expressed in individuals per hectare.

Species	Garotes 1	Garotes 2	Av. Garotes
Boops boops	38.77	46.83	42.80
Maërl rhodoliths	43.56	0	21.78
Spicara smaris	40.80	0.10	20.45
Echinus melo	0	9.50	4.75
Octopus vulgaris	3.68	0	1.84
Pagellus erythrinus	0.92	2.14	1.53
Trachurus picturatus	2.61	0	1.30
Antedon mediterranea	0	2.38	1.19
Ophiotrix fragilis	0	2.38	1.19
Scomber scombrus	2.19	0.03	1.11

Table 5. – Abundance (ind. ha^{-1}) and biomass (g ha^{-1}) in each fishing ground of discard species regulated by Article 15 and species with local regulations. Ab, abundance; %Ab, abundance percentage; B, biomass; and %B, percentage of biomass.

		Garotes				Las 40-Capets				Planassa				Fluviana				Malica				Total			
		Ab	%Ab	B	%B	Ab	%Ab	B	%B	Ab	%Ab	B	%B	Ab	%Ab	B	%B	Ab	%Ab	B	%B	Ab	%Ab	B	%B
Art. 15 CE	*M. merluccius*	0	0	0	0	0.37	3.73	19.9	4.52	1.22	17.1	12.1	5.81	1.81	18.1	10.6	4.30	0.22	3.55	5.41	5.12	0.72	4.42	9.60	1.06
	M. barbatus	0.13	0.26	3.24	0.09	0	0	0	0	0.24	3.42	10.43	4.99	1.38	13.8	27.5	11.2	0	0	0	0	0.35	2.13	8.24	0.91
	P. bogaraveo	0.05	0.11	3.19	0.09	0.47	4.83	24.9	5.66	0.72	10.1	40.1	19.2	0.32	3.15	28.8	11.7	0.09	1.49	8.42	7.97	0.33	2.02	21.1	2.32
	P. erythrinus	1.53	3.13	84.54	2.39	0.54	5.57	33.5	7.61	0	0	0	0	0	0	0	0	0	0	0	0	0.41	2.53	23.6	2.60
	S. scombrus	1.11	2.27	77.21	2.18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.22	1.36	15.4	1.70
	T. picturatus	1.30	2.67	89.01	2.51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.26	1.59	17.8	1.96
	T. trachurus	0.02	0.04	0.60	0.02	2.95	30.1	108.5	24.7	0.74	10.3	23.6	11.3	0.08	0.79	3.78	1.54	0	0	0	0	0.76	4.62	27.3	3.01
	N. norvegicus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.27	69.8	46.1	43.7	0.85	5.21	9.23	1.02
	P. longirostris	0	0	0	0	0	0	0	0	1.21	17.0	6.00	2.87	0	0	0	0	0.76	12.4	5.52	5.23	0.39	2.40	2.30	0.25
Local regulations	*T. capellanus*	0	0	0	0	0.52	5.29	6.33	1.44	0.27	3.79	11.7	5.62	3.54	35.4	13.9	5.66	0	0	0	0	0.87	5.29	6.40	0.70
	M. potassou	0	0	0	0	0	0	0	0	2.46	34.5	97.7	46.8	0	0	0	0	0.32	5.26	10.6	10.1	0.56	3.40	21.7	2.39
	L. budegassa	0.05	0.11	4.01	0.11	1.06	10.9	55.8	12.7	0.17	2.39	3.65	1.75	0	0	0	0	0.41	6.64	13.4	12.7	0.34	2.07	15.4	1.69
	L. piscatorius	0	0	0	0	0.46	4.71	32.96	7.49	0.11	1.49	3.47	1.66	1.42	14.2	16.0	6.51	0.01	0.24	0.25	0.24	0.40	2.44	10.5	1.16
	B. boops	42.8	87.7	2726	77.0	3.42	34.9	151	35.9	0	0	0	0	1.45	14.6	145.3	59.1	0	0	0	0	9.53	58.2	605.9	66.7
	O. vulgaris	1.84	3.77	552	15.60	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0.62	15.8	15.0	0.38	2.29	113.6	12.5

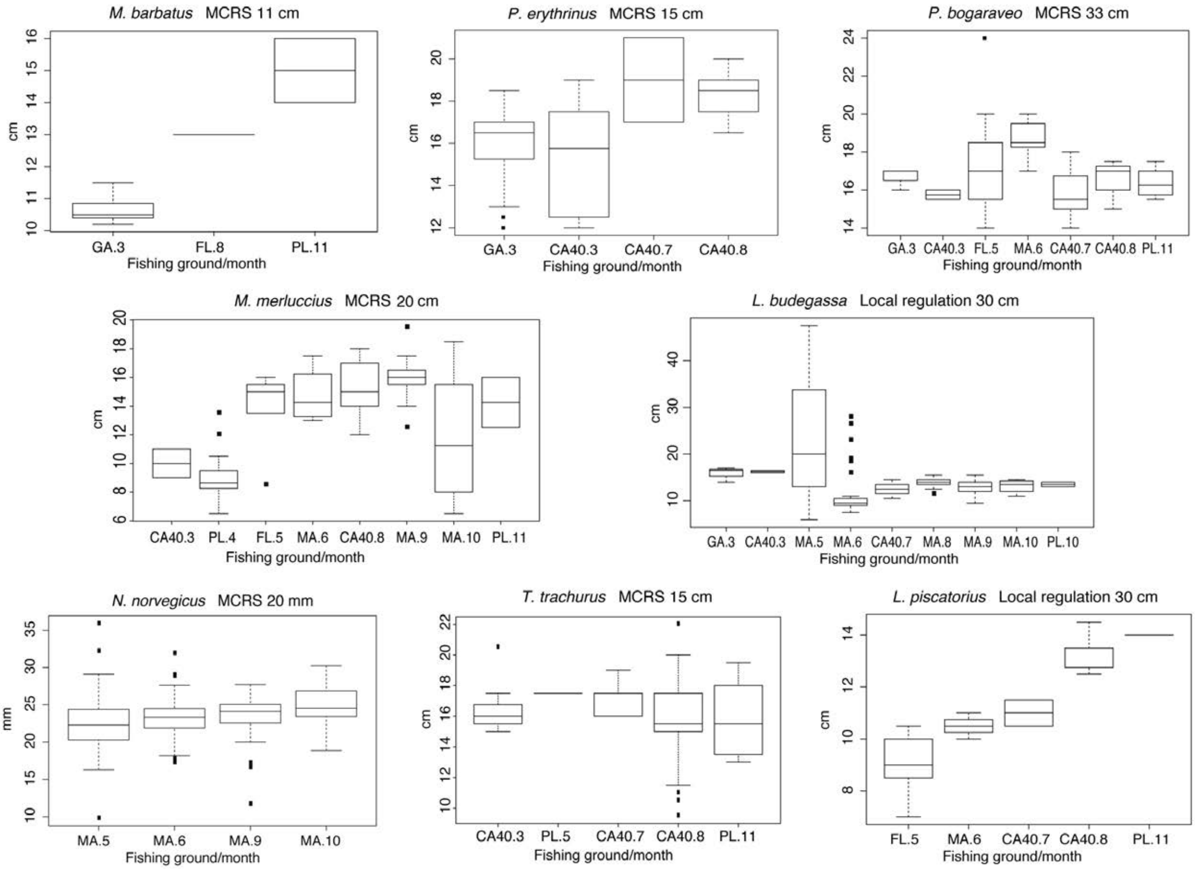

Fig. 3. – Monthly (in number) size distribution of the regulated species discarded from each fishing ground (Ga, Garotes; Pl, Planassa; Fl, Fluviana; CA40, Las 40-Capets; MA, Malica).

Species abundance at Garotes showed that the average abundance of maërl rhodoliths was one of the largest, with 21.78 ind. ha^{-1} (Table 4). The presence of maërl rhodoliths was located exclusively in the area corresponding to one of the two hauls carried out over a depth range of 54 to 70 m with rhodolith abundance of 43.56 ind. ha^{-1}. Other abundant species in the discards of the Garotes fishing ground were *Boops boops* and *Spicara smaris*.

Regulated discard characterization

From the total hauls analysed, we observed 15 discarded regulated species: 9 regulated by MCRS and 6 regulated locally by the Spanish or the Catalan government (Table 5). These species include 12 fish, two crustaceans and one cephalopod.

The locally regulated species *Boops boops* was the most discarded species, with a total of 58.21% abundance, well above the discarded percentage of other species, among which only *Trisopterus capelanus* and *Nephrops norvegicus* exceeded 5%. *Merluccius merluccius*, *Lophius budegassa* and *Trachurus trachurus* were discarded in all fishing grounds except one.

In Garotes, species regulated by MCRS such as *Pagellus erythrinus*, *Mullus barbatus* or *Pagellus bogaraveo* were discarded, although with a percentage of abundance much lower than *Boops boops*, which was discarded in 87.45% of cases. As in Garotes, the most discarded species in Las 40-Capets was *Boops boops*, which, like *Trachurus trachurus*, exceeded 30% of discarded abundance at this fishing ground. On the other hand, in Planassa, *Micromesistius potassou*, *Merluccius merluccius* and *Pagellus bogaraveo* were the most discarded regulated species, accounting for 34.46%, 17.08% and 3.42% of the abundance, respectively. In Fluviana, the discard of the MCRS regulated species *Mullus barbatus* and *Pagellus bogaraveo* accounted for close to 23% of the total biomass discarded. Finally, it is noteworthy that the most discarded species in Malica was *Nephrops norvegicus*, with 69.83% abundance and 43.67% biomass (Table 5). Regarding the size of the discarded regulated species, Figure 3 shows the size ranges of the eight species that were important in the study area because of their commercial interest. Only the genus *Lophius* is regulated at the local level. *Pagellus bogaraveo* was discarded in all fishing grounds due to its small size, and *Lophius piscatorius* and *Merluccius merluccius* were discarded for their small size in all fishing grounds except Garotes, where neither were discarded (Fig. 3). In addition, the fraction of *Lophius piscatorius* discarded grew over time, while *Merluccius merluccius* was discarded during all sampling months.

Nephrops norvegicus was discarded exclusively in Malica and showed an increase in the size of discarded individuals over time. *Mullus barbatus* and *Lophius budegassa* also showed an increase in size over time.

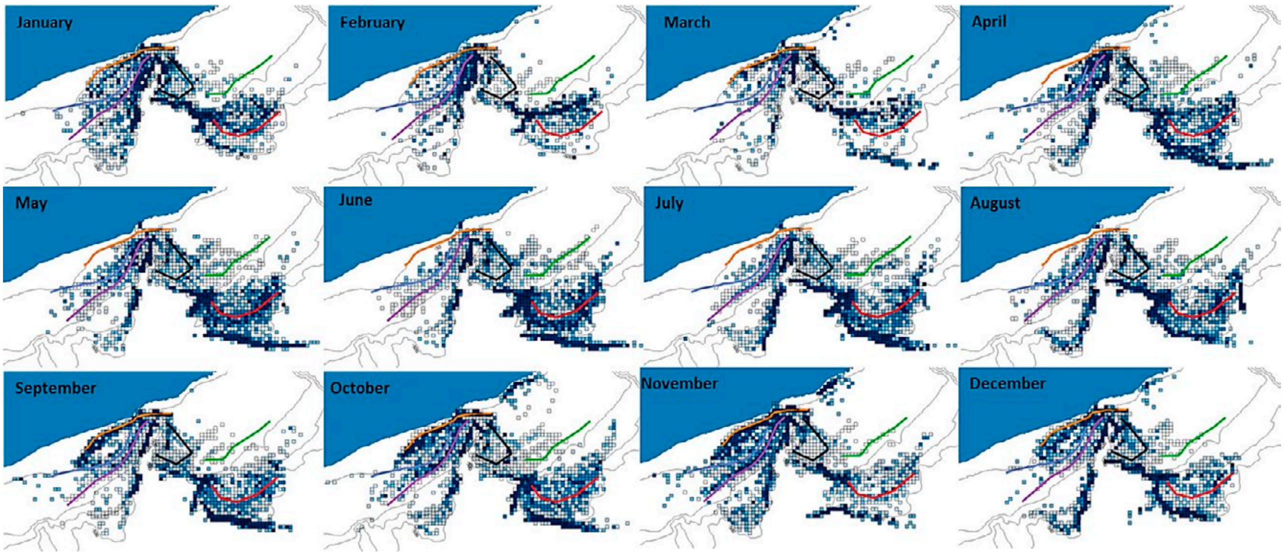

Fig. 4. – Monthly fishing effort estimates of the Blanes trawl fleet (2012-2014) and the locations of the fishing grounds studied (red, Malica; green, Fluviana; black, Planassa; purple, Las 40; light blue, Capets; and orange, Garotes).

Fishing effort dynamics

From 2012 to 2014 at the fishing grounds adjacent to Blanes port, trawl fleet dynamics were described, and the fishing effort was estimated per month for all fishing activity areas (Fig. 4).

The fishing ground Malica, located on the upper slope, endured intense fishing activity throughout the year, although fishing effort increased specifically in May and June. In Planassa and Fluviana, there was a fairly continuous fishing effort throughout the year, although it was less intense than in Malica. In addition, Fluviana was the fishing ground least frequently exploited by the fleet. Finally, Garotes, Capets and Las 40 showed a clear seasonal variation in fishing effort, with practically no fishing effort during some months of the year in Garotes. However, in September, there was a sudden increase in fishing effort at Garotes, which continued until December and then progressively decreased until April. Finally, Capets and Las 40 showed low but continued fishing effort throughout the year, except from July to November, when it increased significantly.

Link between fishing effort dynamics and regulated discard

The fishing effort at Las 40-Capets was significantly lower in March than in July and August (Fig. 5).

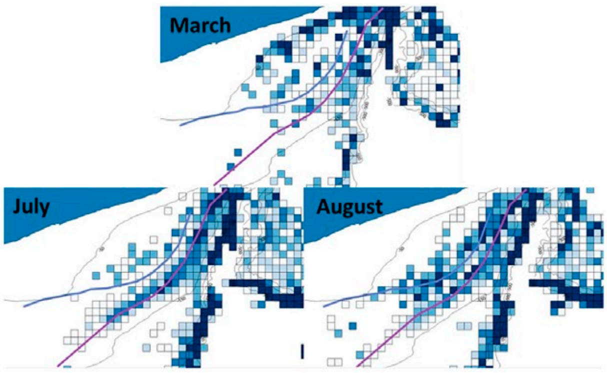

Fig. 5. – Fishing effort dynamics detail in Las 40-Capets for March, July and August.

Table 6. – Average biomass (g ha^{-1}) and abundance (ind. ha^{-1}) of species affected by the landing obligation for the months shown in Figure 5.

Las 40-Capets	Av. March		Av. July-August	
	Abundance	Biomass	Abundance	Biomass
Merluccius merluccius	0.41	3.68	0.34	30.72
Pagellus bogaraveo	0.09	0.004	0.73	41.47
Pagellus erythrinus	0.92	46.47	0.29	24.81
Trachurus trachurus	1.97	78.6	3.6	128.49
Total	3.39	128.75	4.96	225.49

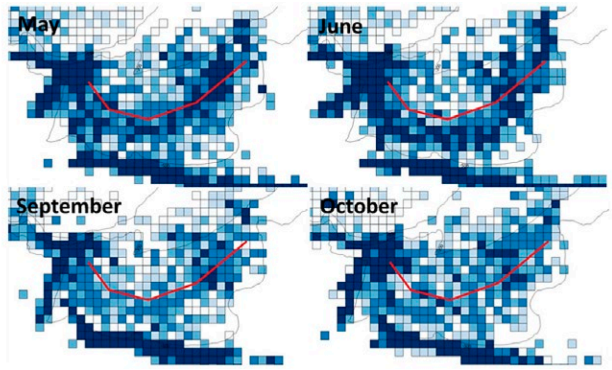

Fig. 6. – Fishing effort dynamics detail in Malica for May, June, September and October.

Table 7. – Average biomass (g ha^{-1}) and abundance (ind. ha^{-1}) of species affected by the landing obligation for the months shown in Figure 6.

Malica	Av. May-June		Av. September-October	
	Abundace	Biomass	Abundance	Biomass
Merluccius merluccius	0.07	1.35	0.52	10.14
Pagellus bogaraveo	0.14	12.62	0	0
Nephrops norvegicus	5.12	56.24	2.57	19.44
Parapenaeus longirostris	0.98	6.77	0.31	2.27
Total	6.3	76.99	3.4	31.85

This increase coincided with an increase in the regulated MCRS discard biomass, which was practically double that in March (Table 6). At the species level, it occurred with practically the same pattern. Most of the regulated species were discarded in greater numbers and biomass in July and August. This was the case for the target species *Pagellus bogaraveo*, of which only 0.004 g ha^{-1} were discarded in March, while in July and August, 41.47 g ha^{-1} were discarded.

In Malica, the total average discard biomass and abundance of regulated species was higher in May and June than in September and October (Table 7). For example, an average of 56.24 g ha^{-1} of *Nephrops norvegicus* was discarded in May and June, while an average of 19.44 g ha^{-1} was discarded in September and October, coinciding with a decrease in fishing effort in these last two months (Fig. 6).

DISCUSSION

The present work has analysed the captures of commercial trawl vessels, emphasizing the links between the discard fraction, specific species affected by the new European regulation on landing obligations and by local regulations, and the seasonal and spatial distribution of the fishing effort of the Blanes trawl fleet. Our final goal was to link these two types of information to propose measures that can help minimize or avoid unwanted catches.

Fishermen develop dynamic fishing strategies as an adaptive response to changes in resource abundance, environmental conditions and market or regulatory constraints (Martín et al. 2014). The Blanes fleet fishing effort showed two different behaviours: a continuous fishing effort in the canyon and upper slope zones, which corresponds to specialist behaviour on fishing grounds with *Aristeus antennatus* and *Nephrops norvegicus* as the target species; and a discontinuous fishing effort on most of the continental shelf fishing grounds, which corresponds to the generalist behaviour where there were several target species, such as *Merluccius merluccius*, *Mullus* spp., or *Lophius* spp. The knowledge of these dynamics is fundamental for the effective management of fisheries (Salas et al. 2004). Similar to the findings of previous works on the Blanes trawl fleet (Sanchez et al. 2004, Tsagarakis et al. 2014), this specialist or generalist behaviour was related to the discard amount, which was significantly higher on the continental shelf than on the upper slope (Table 2). Discard heterogeneity was also related to higher discard amounts, which were predominantly located on the continental shelf, with a similarity of between 15% and 40% (Table 3), while the most homogeneous fishing ground, located on the upper slope, showed less discard and an average similarity close to 60%.

Knowledge on the distribution of fishing activities should be followed by the characterization of the fished habitats (Demestre et al. 2000). Discard analysis by species revealed the existence of two especially productive but vulnerable Mediterranean habitats.

First, in Garotes, an area with maërl rhodoliths was found. This could indicate that in the past, there was an active maërl bed that over time has been degraded as a result of fishing pressure. Although maërl is protected in Annex I of the Habitat Directive (EU Dir. 92/43/EEC), fishing pressure is still exerted on maërl habitat, here and in other Mediterranean areas (Demestre et al. 2017). In the western Mediterranean, maërl bottoms can reach 90 or 100 m depth (Basso 1996), and in Garotes, rhodoliths were found in the hauls carried out at lower depths, between 54 and 70 m (Table 4), where the fishing effort intensity was very low for five months out of the year (Fig. 4). However, there was a constant fishing effort in deeper areas of this fishing ground, between 80 and 107 m depth, where maërl rhodoliths were not found. It is possible that the maërl, due to its vulnerability to trawling (De Juan et al. 2013, Barberá et al. 2012), disappeared completely from deep areas of Garotes, surviving only in areas with lower fishing pressure. Second, areas with *Leptometra phalangium* crinoid aggregations were also found in two adjacent fishing grounds, Planassa and Fluviana. These fishing grounds showed the largest biomass of unregulated discards (Table 2), high heterogeneity (Table 3) and moderate but continuous fishing effort throughout the year. In the three fishing grounds where commercial species below the legal size (such as *Merluccius merluccius, Lophius* spp., and *Pagellus* spp.) were captured, catches showed that they function as nursery areas, as is confirmed in other studies (Hall-Spencer et al. 2003, Steller et al. 2003, Colloca et al. 2004).

A high similarity between the Las 40 and Capets fishing grounds is suggested by the close association of their hauls in MDS space (Fig. 2). Their discards were mainly composed of echinoderms such as *Ophiura texturata* and *Echinus melo* and the locally regulated fish *Boops boops,* but juveniles of several commercial species, such as *Merluccius merluccius* and *Pagellus bogaraveo,* were also found (Fig. 3), suggesting that these fishing grounds could also function as nursery areas for some commercial fish species.

Although in a higher bathymetric range, a previous study carried out in the Catalan Sea (Maynou and Cartes 2000) revealed a *Nephrops norvegicus* incidence of 1.8 ind. ha^{-1} for the total catch. In our work *Nephrops norvegicus* discard had a considerable incidence in Malica, where with 4.27 ind. ha^{-1} it was the most discarded species, mainly due to its small size. This commercial species is regulated by an MCRS and avoiding the capture of small individuals is imperative to improve fishery management (Méhault et al. 2016). In addition, Norway lobster showed good survival potential in several studies (Campos et al. 2015, Méhault et al. 2016), and this species could be exempt from the landing obligation because of its high survival (Article 15 of EU Reg. 1380/2013). Sorting methods to improve the survival of the discards of this species in the Mediterranean should be adopted, such as sorting tables to expedite discard activities (Garcia-de-Vinuesa et al. 2017).

The discarding behaviour of the Blanes trawler fleet is related to the biology of some species regulated by

MCRS. The period of greatest reproductive activity of many Mediterranean commercial fish species, such as *Merluccius merluccius*, *Mullus barbatus*, *Mullus surmuletus*, *Pagellus bogaraveo*, *Pagellus erythrinus* and *Trachurus trachurus*, occurs between late spring and late autumn (Recasens et al. 2008, Tsikliras et al. 2014, Carbonara et al. 2015), and there was a significant increase in fishing effort in autumn and winter at several of the continental shelf fishing grounds studied, corresponding with the season of recruitment of these animals. This was the case for Garotes, where the fishing effort increased from September to April and discarding increased significantly in March for *Mullus barbatus*, *Pagellus erythrinus* and *Pagellus bogaraveo* (Fig. 3) below the MCRS. In Las 40 and Capets, two species of the genus *Pagellus* plus *Merluccius merluccius* and *Trachurus trachurus* were discarded mainly because they did not reach the MCRS (Fig. 3), and the total discarded biomass of these regulated species at the end of summer was practically double that in March (Table 6). On the other hand, in Malica, the smallest individuals of *Nephrops norvegicus* were discarded almost three times more often between May and June, when fishing effort increased, than in September and October (Table 7). Finally, although there was no significant seasonal change in fishing effort at fishing grounds with crinoid aggregations, MCRS-regulated species such as *Mullus barbatus*, *Merluccius merluccius*, *Pagellus bogaraveo* and *Trachurus trachurus* were discarded, the last three below their MCRS. Due to the costs in time and money that the landing obligation entails, one of the expected positive consequences can be the increased interest of fishermen in avoiding areas where unwanted species are caught, thus improving fishing efficiency (Vilela and Bellido 2015).

Species regulated at the local level that are also commercially important include those of the genus *Lophius* spp. which comprise two target species in the region that were discarded in all the fishing grounds studied (almost always under the local minimum legal size) and *Micromesistius poutassou*, *Trisopterus capelanus* and *Octopus vulgaris*, which are accessory species to the Blanes trawl fleet. *Boops boops* was the only non-commercial regulated species that we found, and it was the most discarded species.

CONCLUSIONS

The joint study of catch focusing especially on the discard fraction and fishing effort dynamics provides a useful tool for improving the management of trawling fisheries and particularly for avoiding unwanted catches. The presence of maërl in Garotes together with the large discard rates and the obligation to land six species affected by MCRS suggests that this area could be a good candidate for establishing a permanent no-take zone to avoid the problem of unwanted catches and prevent further habitat degradation. Additionally, it is demonstrated that, as in Garotes, fishing effort on Las 40 and Capets increased during recruitment months for commercial species affected by the landing obligation. Thus, carrying out seasonal closures in these fishing grounds is recommended, and although no seasonal pattern was found in the behaviour of the fleet in fishing grounds with crinoid aggregations, seasonal closures could be carried out during the recruitment season of discarded species regulated by MCRS such as *Merluccius merluccius* and *Mullus barbatus* or species regulated locally such as *Lophius* spp. to avoid unwanted catches. These closures would be more beneficial in late spring or summer, but not in February, as has already been adopted in the area by internal agreement among the fishermen. Also, de *minimis* exemption could be applied for hake and red mullet, up to a maximum of 7% of the total annual catches in 2018 and 6% in 2019 (EU Reg. 2017/86) in all fishing grounds, but this would only be a short-term solution.

Finally, in Malica, the possibility of reducing fishing effort in the months in which smaller individuals of *Nephrops norvegicus* were discarded should be studied, particularly in the months of May and June.

ACKNOWLEDGEMENTS

This work was funded by the research project MINOUW (H2020-SFS-2014-2) from the European Commission (contract nº 634495). We also acknowledge the help of the vessels' crew during sampling and the data provided by MAGRAMA, which were indispensable for meeting the objectives of this work.

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Discards regulation vs Mediterranean fisheries sustainability
M. Demestre and F. Maynou (eds)

SCIENTIA MARINA 82S1
December 2018, 189-198, Barcelona (Spain)
ISSN-L: 0214-8358
https://doi.org/10.3989/scimar.04784.28A

Ecological importance of survival of unwanted invertebrates discarded in different NW Mediterranean trawl fisheries

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Summary: There is currently very little information on the survival of discards of unwanted and unregulated catches of invertebrates after the stresses caused by capture. A great number of the unregulated invertebrate species form the basis of essential fish habitats for important fisheries resources such as hake, red mullet and cuttlefish. Thus, data on their survival after discarding may help to interpret the role of these species within the benthic ecosystems. Furthermore, descriptor 6 of the Marine Strategy Framework Directive (EU Directive 2008/56/E) foresees maintaining sea floor integrity at a level that ensures that the structure and functions of the ecosystems are safeguarded, and Article 7(d) of the Common Fisheries Policy (EU Reg. 1380/2013) foresees the implementation of management measures for fishing with low impact on the marine ecosystem and fishery resources. Survival measurements by direct recovery of tagged discarded species are not effective in bottom trawl fisheries, for which alternative studies such as semi-quantitative measures obtained on board prior to discarding can be considered as appropriate for mortality estimation. The present work assessed the survival of unwanted species using a semi-quantitative assessment on the deck of trawlers and at the laboratory for a period of 96 hours in two Mediterranean areas (the Catalan coast and the Ligurian and Northern Tyrrhenian seas). A high number of discarded invertebrates showed a high percentage of survival (>70%) in both assessments. The results can be used to provide information that can help to achieve higher survival levels of discarded specimens and enhance the productivity of fishing grounds by increasing the health of benthic ecosystems.

Keywords: discard survival; invertebrates; mortality estimation; vitality levels; trawl fishery; Mediterranean.

Importancia ecológica de la supervivencia de invertebrados no-deseados descartados en distintas pesquerías de arrastre del Mediterráneo nor-occidental

Resumen: Actualmente, hay muy poca información sobre la supervivencia del descarte de los invertebrados no-deseados y no-regulados después del stress de la captura. Un gran número de especies de estos invertebrados son básicas para los hábitats esenciales de importantes recursos pesqueros como la merluza, el salmonete o la sepia. Por lo tanto, información sobre su supervivencia al ser descartados pueden ayudar a interpretar el papel de estas especies dentro de los ecosistemas bentónicos. Además, el punto 6 de la Directiva Marco de Estrategia Marina (MSFD, EU Directive 2008/56/E) prevé mantener la integridad del fondo marino a un nivel que garantice la protección de la estructura y de las funciones de los ecosistemas, y el artículo 7 (d) de la Política Pesquera Común (PPC EU Reg. 1380/2013) prevé la implementación de medidas de gestión para la pesca, que tengan bajo impacto tanto en el ecosistema marino como en los recursos pesqueros. En el caso de las pescas de arrastre de fondo, no es efectiva la estimación de la supervivencia a partir del método directo de captura-recapture de las especies del descarte marcadas, por lo que los estudios alternativos, como las medidas semicuantitativas obtenidas a bordo antes del descarte, pueden considerarse una estimación de la mortalidad apropiada. El presente trabajo evaluó la supervivencia del descarte de especies no-deseadas utilizando una Evaluación Semicuantitativa (SQA) mediante dos estudios: uno sobre la cubierta de los arrastreros y el otro en laboratorio durante un período de 96 horas, en dos áreas del Mediterráneo, las costas Catalanas y en los mares de Liguria y del Tirreno Norte. Los resultados mostraron en ambos estudios, que un alto número de invertebrados descartados tenía un alto porcentaje de supervivencia (>70%). El propósito de estos resultados es proporcionar información que puede ayudar a alcanzar niveles de supervivencia más altos de los individuos descartados. Al mismo tiempo, se espera que con esta mejora se consiga potenciar la productividad de los caladeros al aumentar la salud de los ecosistemas bentónicos.

Palabras clave: supervivencia del descarte; invertebrados; estimación de mortalidad; estados de vitalidad; arrastre, Mediterráneo.

Citation/Cómo citar este artículo: Demestre M., Sartor P., Garcia-de-Vinuesa A., Sbrana M., Maynou F., Massaro A. 2018. Ecological importance of survival of unwanted invertebrates discarded in different NW Mediterranean trawl fisheries. Sci. Mar. 82S1: 189-198. https://doi.org/10.3989/scimar.04784.28A

Editor: P. Martín.

Received: March 21, 2018. **Accepted:** July 19, 2018. **Published:** November 5, 2018.

INTRODUCTION

Mediterranean fisheries are characterized by a high rate of unwanted catches and a great number of marine organisms that are discarded at sea (Lleonart 2015, Tsagarakis et al. 2014). One of the fishing methods that produces most discards is otter bottom trawling, which is also one of the least selective fishing gears. The discards include both species with non-commercial value and marketable species that are undersized or of low value. Technical regulations, such as the introduction of the 40-mm square mesh or the 50-mm diamond mesh in the cod-end (EC 1967/2006) can reduce discards to some extent, but cannot solve the impacts of bottom trawling on habitats and benthic communities.

The investigated areas were the Catalan coast, corresponding to FAO division 37.1.1, Geographical Sub-Area 6 (GSA06), and the Ligurian and northern Tyrrhenian seas, corresponding to FAO division 37.1.3, Geographical Sub-Area 9 (GSA09), both comprising chronically exploited fishing grounds. In the last ten years the demersal fisheries carried out mainly by bottom trawl fleets in the two areas accounted for about 40% of the total landings and 70% of the economic value (STECF 2016).

A large fraction of this discarded biomass (30%-50% of the total biomass caught) is composed of species of commercial interest (small-sized or damaged specimens), while the remaining fraction is composed of species with low or no economic value (Machias et al. 2001, Sánchez et al. 2004, 2007). Furthermore, trawl fleets operate in a great variety of soft habitats (e.g. muddy-sand, sandy-muddy, mud, sandy-gravel, sand), so discards are characterized by extremely high species diversity with a high percentage of non-commercial species, some of which are macroinvertebrates (echinoderms, crustaceans, poriferans, ascidians, cnidarians, bryozoans, bivalves and gastropods). In many cases the discarded species belong to sensitive benthic habitats, such as maërl or crinoid beds.

The impact of bottom trawling on benthic habitats and communities and demersal species is little known. The impact depends on the fishing activity (Martín et al. 2014) and can create changes in the ecological functioning of benthic components that have important repercussions on the exploited populations (de Juan et al. 2007, Frid 2011, Hewitt et al. 2008).

The European Marine Strategy Framework Directive (EU 2008/56/E) encourages member states to move towards an ecosystem-based fishery management in order to protect the goods and services that marine ecosystems provide. Therefore, it is important to take into account the link between benthic communities and habitats and fisheries resources, because a great number of ecological interactions may be adversely impacted by fishing. The capture of benthic invertebrates and their discarding at sea will impact benthic habitats to a certain degree, depending on the post-release survival of each species. The survival of habitat-structuring invertebrates, such as crinoids and echinoderms, can help to maintain the good status of the essential fish habitats where the most important commercial resources, such as European hake, red mullet, spiny lobster and cuttlefish, use them as areas of nursery, recruitment or growth (Abella et al. 2008, Colloca et al. 2009).

There is currently very little information on the survival of unwanted and unregulated invertebrates after the stresses of being captured, handled and discarded. The specific biological characteristics make an organism more or less vulnerable to different stressors of the capture method and release process (de Juan and Demestre 2012). Other factors affecting the survival of released animals are related to the handling practices during the sorting and release processes and to the environmental conditions during capture, hauling on board and sorting, such as hypoxia and temperature (Bergmann et al. 2001, Giomi et al. 2008, Tsagarakis et al. 2017).

Some unwanted and unregulated invertebrates such as crinoids and ophiuroids form the basis of essential fish habitats for commercial species such as hake and red mullet. Robust information on discard survival after fishing and release to the seabed can improve the interpretation of the role of unregulated invertebrates on the benthos (Benoît et al. 2012).

The main objective of this paper was to estimate survival rates of invertebrates discarded from trawlers working in two northwestern Mediterranean areas, the Catalan coast and the Ligurian and northern Tyrrhenian seas. The study focused on unwanted invertebrates which belong to the unregulated species and are likely to continue to be released after capture. To estimate the vitality rates, a vitality assessment on the captured organisms was carried out under normal fishing activity of the trawl fleets in both selected areas. The approach was developed using a semi-quantitative assessment (SQA) (ICES 2014) according to Benoît et al. (2012). Two different procedures of survival estimation were developed, considering first the survival on the deck of trawlers and second the long-term survival at the laboratory with captive observations. The survival rate of the discarded fraction in the trawl catch can be used to propose man-

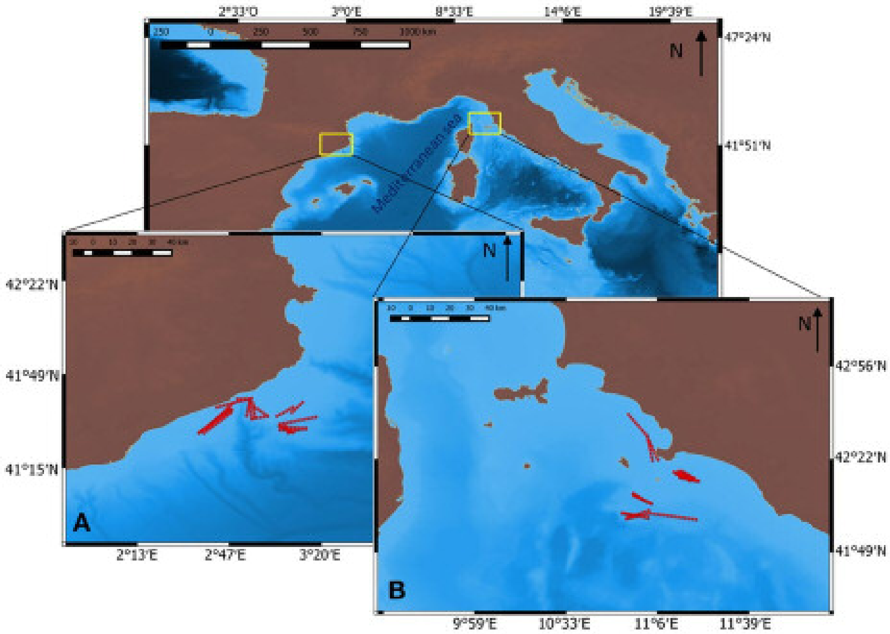

Fig. 1. – Study areas: A, Catalan coast; and B, Ligurian and northern Tyrrhenian seas. Red lines indicate hauls in the selected fishing grounds.

agement based on better control of discards or spatial restrictions to trawling that may accompany specific management plans based on conserving the functionality and health of benthic ecosystems.

MATERIALS AND METHODS

Study areas and sampling activities

The study was carried out in two NW Mediterranean trawl fishing areas, the Catalan coast (GSA 6), from March 2016 to February 2017, and the Ligurian and northern Tyrrhenian seas (GSA 9), from November 2016 to February 2017. Data were collected during fishing trips on board commercial vessels performed on a monthly basis.

Trawl sampling in the Catalan coast area was performed on board four different trawlers in five fishing grounds (Garotes, Las 40, Capets, Planassa and Malica) adjacent to the port of Blanes. The depth range was between 50 and 494 m, with a total of 23 hauls (Fig. 1A; Table 1). In the Ligurian and northern Tyrrhenian seas, 22 commercial hauls were carried out in a bathymetric range of 85-470 m in the Monte Argentario area (Fig. 1B; Table 1).

Table S1 of the Supplementary Material details the main characteristics and environmental data of each haul in the two selected areas. In both areas the average haul duration was about two hours.

At the end of each haul the trawl gear was retrieved on board and the cod-end was opened on the deck following the normal commercial fishing practices. After that, prior to sorting the catch into commercial and discard fractions, the net was shot for a new haul. Depending on the depth, this process took 10 to 25 minutes. During the fishing trips, there was no interference by the researchers on board with the habitual modus operandi of the fishermen in the daily fishing activity (position, duration, sorting, etc.) and the sorting processes of the catch, which lasted 20-30 minutes depending on the capture.

Survival experiments

The hauls considered for survival analysis were 4 on the Catalan coast and 19 in the Ligurian and northern Tyrrhenian seas (Supplementary material Table S1A). The average depth range was between 99 and 362 m on the Catalan coast and between 84 and 470 m in the Ligurian and northern Tyrrhenian seas. The

Table 1. – General information on trawl sampling in the study areas.

Study area	Fishing ground	No Hauls	Min. Depth (m)	Max. Depth (m)	Target species
Catalan coast (GSA06)	Las 40	3	85	120	Red mullet, monkfish, hake, octopus and sea cucumber
	Capets	2	70	113	Red mullet, monkfish, hake, octopus and sea cucumber
	Planassa	6	86	318	Red mullet, sea cucumber, hake and monkfish
	Garotes	2	55	107	Red mullet and pandora
	Malica	9	195	494	Norway lobster
Ligurian and northern Tyrrhenian seas (GSA09)	Argentario	22	85	470	Hake, red mullet, horned octopus and deep-water pink shrimp

Table 2. – Description of vitality levels of invertebrate organisms for a semi-quantitative assessment approach by groups of likely animals (From ICES 2014 and Demestre 2012).

Vitality levels	Code	Crustaceans	Echinoderms (Ophiuroidea and Asteroidea)	Echinoderms (Echinoidea)	Mollusca	Sessile (ascidians, corals, hydroids, etc.)
Excellent	1	Continued movement; no external injury.	Continued movement; no external injury.	Continued movement; no external injury.	Continued movement; no external injury.	Shape and size similar to natural state. No external injury.
Good	2	Weak movement; responds to contact; no external injury or superficial cuts on the exoskeleton or antennae.	Weak movement; responds to contact; no external injury or superficial cuts in limbs.	Weak movement; responds to contact; no external injury or few broken spines	Weak movement; responds to contact; scraping of shell or moderate loss of tegument.	Size and shape moderately different to natural state; moderate cuts or abrasions.
Poor	3	No apparent movement, but can move antennae or maxillipeds; loss of a member or deep cuts.	No apparent movement, but can move tube feet; deep cuts and loss of all or part of extremities.	No apparent movement, but can move tube feet; external injury and many broken spines.	No apparent movement, but can move feet, loss of parts of the shell or limbs.	Shape and size different to natural state; surface or serious cuts or abrasions; loss of body parts.
Dying or dead	4	No movement; does not respond to contact.	No movement; does not respond to contact; loss of central parts of body.	No movement; does not respond to contact; or broken shell.	No movement; does not respond to contact; or broken shell.	Loss of central parts of the body.

hauls were carried out on both the continental shelf and the upper slope, with a standard deviation of 117.66 and 152.89 m, respectively. The complexity of the experiment forced us to limit the number of hauls. While the catch was being sorted manually on deck by the fishermen, in both areas the vitality of the unregulated, non-commercial invertebrates was assessed just before the species were discarded. The SQA (ICES 2014) was performed by means of indicators of state of vitality according to mobility, injuries and lesions suffered by the organisms due to the fishing activity. To estimate the vitality of each individual, a categorical assessment scale of four vitality levels (VL) was applied: 1 (excellent), 2 (good), 3 (poor) and 4 (dying or dead) (Benoît et al. 2012, ICES 2017). A detailed explanation of each VL is presented in Table 2.

Two approaches to performing the survival experiments were developed: i) direct survival estimation on deck and ii) survival estimation at the laboratory for a period of 96 hours. In both study areas the studied invertebrates are only captured by trawling. Because of the challenges of obtaining viable control samples with other gears, the individuals who were classified in excellent state of vitality (Table 1) at the start of the captive experiment (time T0, just as it was being released on deck) were taken as pseudo-controls for each haul (ICES 2014).

Survival estimation on deck

In both areas the immediate survival on deck was estimated following the same methodology. For the selected species, as many individuals as possible were taken and one of the four VLs was assigned to each one using the SQA (Table 2). The selection process was carried out only during the first 30 minutes after opening the net on the deck, starting before the gear was shot for a new haul. It was done as quickly as possible to decrease as far as possible the time of air exposure on deck.

Survival at the laboratory

The long-term survival rate was estimated for 96 h to achieve a deeper knowledge of the actual survival of the invertebrates discarded. It was only performed in the Catalan coast area. To analyse survival at the laboratory, the individuals of the selected species were sampled from the last daily haul, just when the catch was laid on deck and prior to sorting, but only during the first 30 minutes, as in the previous case. The VL was assessed according to the SQA (Table 2). The four possible VLs were observed for each specimen, which were individually introduced in four white containers (one for each VL), with running sea surface water to avoid hypoxia. The maximum number of selected animals was that which could be introduced in each container without causing stress. A total of 324 individuals from 22 species of invertebrates (10 echinoderms, 8 crustaceans, 2 cnidarians and 2 ascidians) were sampled but only the 6 most abundant species were selected for this survival assessment.

Survival at the laboratory was estimated for 96 hours in an aquarium at the ICM laboratory by applying an SQA. A total of ten time survival observations (T) were carried out during the experiment (from T0 to T9). The first observation, time T0, just as animals were being released on deck, was executed on board. Individuals were selected for a maximum time of 30 minutes, and each one was introduced successively into the containers, as explained above. The second observation, T1 (6 h), was performed just before each individual was transferred to the aquariums at the laboratory. The individuals that were in VL 4 (dead or moribund) were removed to avoid contamination in aquariums, but were accounted for. The following eight observation times, from T2 (18 h) to T9 (96 h), were made on the specimens placed in the aquariums, with a periodicity of 12 h until the study had lasted for 96 h. The aquariums were divided into three sections for each VL, 1, 2 and 3, and no more than ten individuals were introduced per section. The time of the transport from the sea to the aquariums was a maximum of 2 hours and the animals were on the white plastic containers with oxygen pills during the whole transportation time.

The natural environment conditions were simulated in the aquariums through an open seawater circuit and water temperature was maintained between 13°C and 14°C, similar to the in situ temperature in the north-western Mediterranean fishing grounds. The photoperiod was adapted to the natural luminosity with black canvas to dim the light. Controls of salinity, nitrates, nitrites and silicates were periodically performed. The whole process was carried out under food abstinence conditions.

Data analysis

The survival on deck was estimated by applying the survival index, which was calculated as the ratio between the number of specimens (VN) with a vitality level of 1 to 4 and the total number of discarded individuals (DN) and was expressed as a percentage.

A Wilcoxon test between the exploratory variables recorded (Supplementary material Table S1) and the survival of invertebrates on deck for the first 30 min on board was carried out. The test analyses the relationship of each variable with survival, comparing the data related to live individuals (VLs 1, 2 and 3) with data of dead individuals (VL 4). Finally, if significant differences were observed between the variable and the survival, the group mean was calculated. The Wilcoxon test was implemented in R 3.4.3 (R Core Team 2017).

Because a seasonal sampling was not performed, variables related to seasonality such air and water temperature were not taken into account. We therefore conducted the analysis only with Depth and Haul Time.

To calculate survival rate for each experiment over 96 h, the Kaplan-Meier analysis was used (Kaplan and Meier 1958). The Kaplan-Meier survival curve is a function of the data only, and in the absence of censored values it follows the proportion of individuals alive at each time interval during the holding phase of the experiment and seeks a point in time when survival stabilizes. Plots were made on six selected species for the three live VLs, showing their 95% confidence intervals. Analyses were conducted with the “survival” package in R 3.4.3 (R Core Team 2017).

Table 3. – Vitality levels (VL) and survival index of discarded invertebrates estimated on deck: A, Catalan coast; B, Ligurian and northern Tyrrhenian seas.

		Species	VL 1	VL 2	VL 3	VL 4	Total alive	Total assessed	Survival index
A, Catalan coast									
Continental shelf	Crinoid bed	*Antedon mediterranea*	19	2	8	0	29	29	100
		Leptometra phalangium	17	37	86	12	140	152	92.11
		Astropecten aranciacus	0	2	4	0	6	6	100
		Echinus melo	4	5	7	5	16	21	76.19
		Cidaris sp.	2	3	7	0	12	12	100
		Spinolambrus macrochelos	3	0	1	0	4	4	100
		Echinaster sepositus	9	3	4	0	16	16	100
	Muddy	*Anseropoda placenta*	0	0	6	0	6	6	100
		Astropecten irregularis	1	1	0	0	2	2	100
		Diazona violacea	4	0	0	0	4	4	100
		Liocarcinus depurator	1	0	1	1	2	3	66.67
		Microcosmus sulcatus	2	0	0	0	2	2	100
		Ophiura texturata	0	0	38	0	38	38	100
		Macropipus tuberculatus	4	0	2	0	6	6	100
Slope	Muddy	*Dardanus arrososor*	5	7	0	0	12	12	100
		Goneplax rhomboides	2	0	0	0	2	2	100
		Monodaeus couchii	1	0	1	0	2	2	100
		Munida intermedia	0	0	4	2	4	6	66.67
		Nephrops norvegicus	72	143	222	354	437	791	55.25
		Total	147	204	387	375	738	1113	66.3
B, Ligurian and northern Tyrrhenian seas									
Continental shelf		*Astropecten aranciacus*	0	0	3	0	3	3	100
		Galeodea spp.	0	84	0	0	84	84	100
		Goneplax rhomboides	7	0	0	236	7	243	2.88
		Macropodia spp.	45	60	0	0	105	105	100
		Medorippe lanata	21	20	6	955	47	1002	4.69
		Ophiura spp.	0	3	0	0	3	3	100
		Parapenaeu slongirostris	10	4	10	519	24	543	4.42
		Processa spp.	0	0	2	0	2	2	100
		Solenocera membranacea	88	134	187	8923	409	9332	4.38
		Squilla mantis	45	103	114	1863	262	2125	12.33
Slope		*Dardanus arrosor*	4	10	0	28	14	42	33.33
		Pagurus spp.	17	17	6	0	40	40	100
		Astropecten irregularis	0	2	2	8	4	12	33.33
		Macropipus tuberculatus	22	31	32	187	85	272	31.25
		Munida intermedia	2	0	4	13	6	19	31.58
		Nephrops norvegicus	2	5	25	173	32	205	15.61
		Pagurus excavatus	5	16	18	452	39	491	7.94
		Paromola cuvieri	0	0	2	0	2	2	100
		Total	268	489	410	13357	1167	14524	46.41

Table 4. – Percentages of the four vitality levels in each study area for the two species of invertebrates subjected to minimum conservation reference sizes. CC, Catalan coast; LTS, Ligurian and northern Tyrrhenian seas.

	N. norvegicus (CC)	*N. norvegicus* (LTS)	*P. longirostris* (LTS)
Excellent (1)	9.10	0.98	1.84
Good (2)	18.08	2.44	0.74
Poor (3)	28.07	12.20	1.84
Dying or dead (4)	44.75	84.39	95.58

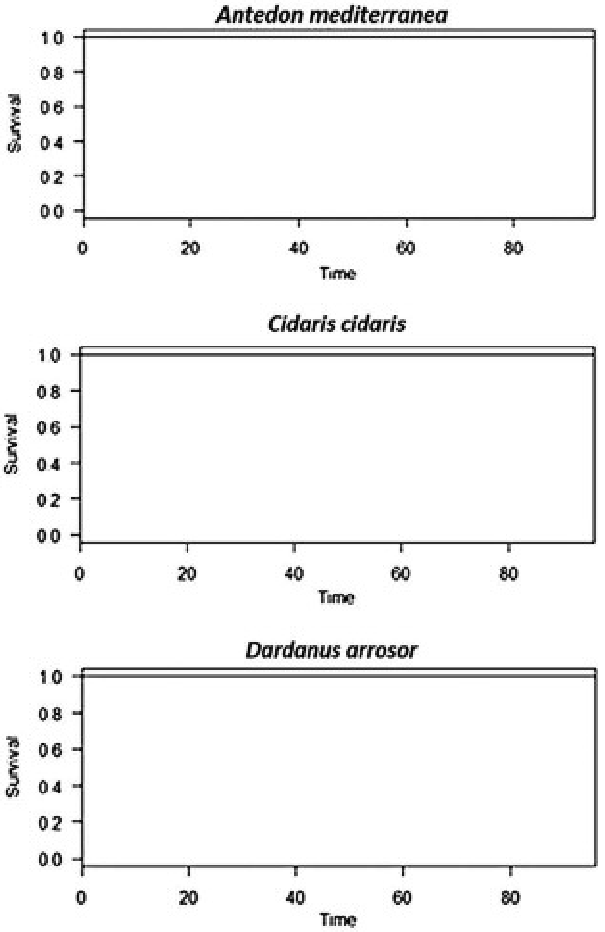

Fig. 2. – Analysis with the K-M model to assess the survival of *Antedon mediterranea*, *Cidaris cidaris* and *Dardanus arrosor.*

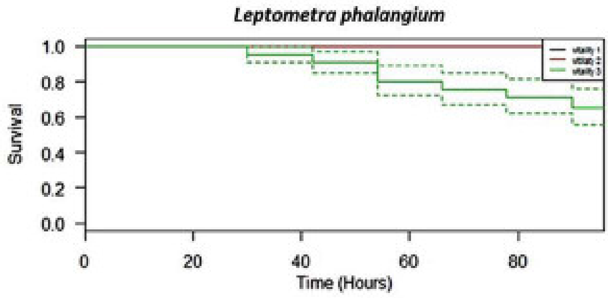

Fig. 3. – K-M model to assess the survival of *Leptometra phalangium* at vitality levels 1, 2 and 3.

RESULTS

Survival on deck

The VLs of discarded invertebrates were identified for each individual of each selected species. Table 3 shows the results of each VL analysed in each study area, according to the continental shelf and slope and the corresponding habitat. From the discarded fraction, the species presented in Table 3 were scored with vitality levels in both study areas. Among the invertebrates captured, only *N. norvegicus* and *P. longirostris* were subject to minimum conservation reference sizes (MCRS) (Council Reg. EC 1967/2006), while the rest of the discarded invertebrates were non-regulated species.

A survival index of 100% was shown by 14 species in the Catalan coast area and 6 in the Ligurian and northern Tyrrhenian seas area, and *Astropecten aranciacus* and the genus *Ophiura* were common in both areas. The species *Munida intermedia*, *Goneplax rhomboids* and *Macropipus tuberculatus* showed a lower survival index in the Ligurian and northern Tyrrhenian seas area, where the processed number of individual was higher and the results were probably more reliable. On the other hand, *N. norvegicus* gave more robust results in the Catalan coast area, where more individuals were analysed.

The percentages of the four vitality levels (VL) of Norway lobster and deep water rose shrimp, the two commercial species subjected to MCRS, are presented in Table 4 for both areas. Values of each VL represent the percentage of the total number of individuals for each level from the total analysed hauls. The Catalan coast area showed the highest percentages of live VLs.

The Wilcoxon test was carried out only with the variables Haul Time and Depth. The results showed no significance between depth and survival. However, the test found significant differences in survival due to Haul time with a p-value $<2.2e-16$ and $W=7898500$. The mean duration of hauls with live animals was 217.39 min, while the mean duration with dead animals was 236.12 min (i.e. a 9% time increase).

Survival at the laboratory

The survival estimation at the laboratory was carried out only for the specimens collected in the Catalan coast study area. The analyses were undertaken only with the invertebrate species with a higher number of individuals scored with VL on deck previous to the discard (Table 3A); a total of six species were analysed. Of the six invertebrates analysed, the three in Figure 2 showed 100% survival for 96 h in the aquarium experiment.

The species *Leptometra phalangium* showed more than 90% survival, and only after 30 h did the percent-

Table 5. Results of K-M model to analyse the survival of *Leptometra phalangium* (A and B), *Ophiura texturata* (C and D), *Echinaster sepositus* (E); n.risk, live animals; n.event, dead animals.

time	n.risk	n.event	survival	std.err	lower 95% CI	upper 95% CI
A. Longitudinal survival over 96 hours and three levels of vitality						
0	152	12	0.921	0.0219	0.879	0.965
30	140	4	0.895	0.0249	0.847	0.945
42	136	4	0.868	0.0274	0.816	0.924
54	132	9	0.809	0.0319	0.749	0.874
66	123	4	0.783	0.0334	0.720	0.851
78	119	4	0.757	0.0348	0.691	0.828
90	115	5	0.724	0.0363	0.656	0.798
B. Mortality events at the laboratory at vitality levels 2 and 3 at T0 (0.0H.=3)						
30	86	4	0.953	0.0227	0.910	0.999
42	82	4	0.907	0.0313	0.848	0.970
54	78	9	0.802	0.0429	0.722	0.891
66	69	4	0.756	0.0463	0.670	0.852
78	65	4	0.709	0.0490	0.620	0.812
90	61	5	0.651	0.0514	0.558	0.760
C. Longitudinal survival over 96 hours at the three vitality levels						
66	38	4	0.895	0.0498	0.802	0.998
78	34	2	0.842	0.0592	0.734	0.966
90	32	2	0.789	0.0661	0.670	0.930
D. Mortality events at the laboratory at vitality level 3 at T3 (T3.28.5H.=3)						
66	36	4	0.889	0.0524	0.792	0.998
78	32	2	0.833	0.0621	0.720	0.964
90	30	2	0.778	0.0693	0.653	0.926
E. Longitudinal survival over 96 hours at the three vitality levels						
6	16	1	0.938	0.0605	0.826	1

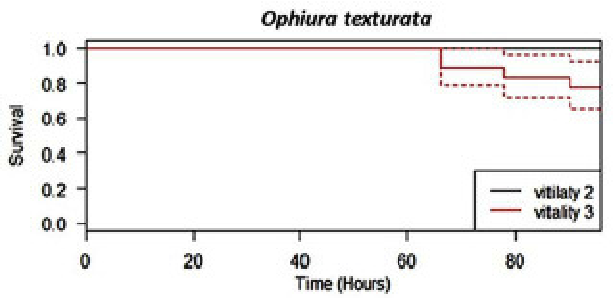

Fig. 4. – K-M model to assess the survival of *Ophuira texturata* at vitality levels 2 and 3.

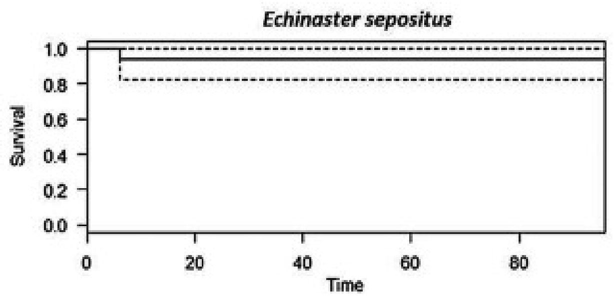

Fig. 5. – K-M model to assess the survival of *Echinaster sepositum* at vitality level 3.

age of mortality increase (Fig. 3; Table 5A, B) in the specimens with the VL 3. VLs 1 and 2 showed no evidence of mortality, but VL 3 showed an evident non-stability of survival.

Similar results were shown for the species *Ophiura texturata*. In this case the first evidence of mortality appeared after 66 h in VL 3, but the percentage of survival was still high (>79 %). VLs 1 and 2 showed no evidence of mortality (Fig. 4, Table 5C, D).

The last species studied in the aquarium was *Echinaster sepositum*, which showed mortality at 6 h of the experiment in VL 3, but maintained a steady survival rate >90% until the end of the experiment (Fig. 5 and Table 5E).

DISCUSSION

This study was carried out with those individuals that showed signs of vitality when arriving on board, which means they were still alive. In fact, there was a low number of specimens that could be assessed, and this may indicate the severe impact of trawling on the seabed and benthic communities (Kaiser and Spencer 1995, Jennings et al. 2001). The preservation of exploited resources is probably the main goal of fishery management, but the perturbation of chronic fishing activity on fishing grounds has negative ecological effects leading to high levels of mortality (DFO 2006, van Denderen et al. 2013).

Several studies have evidenced an improvement in the health of exploited resources when effort limitation and seasonal or temporal closures of trawl fishing activities are implemented (Demestre et al. 2008, Demestre et al. 2015, Pipitone et al. 2000), but the effects at the level of benthic communities remain less well known. The by-catch of invertebrates in bottom trawling yields a high amount of epifauna or infauna that have important functions for the sea floor ecology. For instance, echinoderms or gastropods are important bioturbators and comprise several feeding guilds, such as deposit or filter feeders, or predators (e.g. *Echinus melo, Spatangus purpureus*, *Echinaster sepositus*, *Ophiura texturata*, *Chlamys opercularis*, *Calliostoma granulatum* and *Aporrhais serresianus*). These organisms play an important role in ecosystem function by maintaining or enhancing secondary marine production. They are very sensitive to disturbance and easily destroyed by fishing impact, and their decrease could have lasting consequences for benthos-pelagic processes (Lohrer et al. 2004, Demestre et al. 2017, de Juan et al. 2011), because the good status of the habitats in which the fisheries resources live depends to a large extent on these organisms.

In order to maintain the good status of the sea bottom, one of the priority actions to be taken is to determine the mortality levels of routinely discarded species. A study carried out near the Catalan coast area related the effects of trawl fishing and feeding of the red mullet *Mullus barbatus* (Muntadas et al. 2015), showing negative effects due to changes in benthic functional components in the fishing ground. In areas where there was no fishing (fishing closure areas) the macroinfauna which constitutes the food base for *M. barbatus* was significantly more abundant than in areas disturbed by the trawl. Changes in the habitat structure (homogenization) and functionality of benthic communities caused by fishing can alter the normal supply of food (e.g. polychaetes and crustaceans) for both adult and juvenile red mullet (Fiorentino et al. 2008, Muntadas et al. 2014). Furthermore, as a consequence of the habitat alteration, the characteristics of the seabed that serves as a nursery, spawning or growing habitat could be modified, with possible negative consequences on future recruitment of the species.

The rates of survival shown by invertebrates in both areas investigated in this study showed great variability between VLs of the same species once the individuals had been captured and deposited on the deck of the trawler. Mortality levels also vary from one species to another, depending mainly on the biological and functional traits of each species, such as fragility, emergent or surface position, filter feeding and sedentary motility (Costello et al. 2015, Muntadas et al. 2015). External protection is one of the most relevant traits for increasing survival, as evidenced by the monitoring of VLs on deck to analyse immediate mortality. In both areas the majority of crustaceans remained alive, even reaching percentages of 100%. Invertebrates with regeneration traits such as echinoderms also have a high level of survival.

We went one step further in estimating discarded invertebrate mortality by attempting to identify and separate the injuries of each individual on deck according to its VL. Individuals with VL 1 and 2 at time T0 (time of release on deck) survived on deck until they were released into the sea in a maximum time of 30 min, but those with VL 3 showed low survival on deck. The experiments at the laboratory to analyse survival at 96 h confirmed this behaviour for all analysed species. At the laboratory it was evident that when the survival was not 100% it was because the organism was at VL 3 when released on deck, and in fewer cases at VL 2.

The results of the Wilcoxon test indicated that Haul Time was an important factor for improving organisms' survival on deck. Injuries increased and VL decreased when invertebrates arrive on deck after long hauls, as was observed in the continental shell hauls, which showed a higher survival of species of crinoids and crustaceans (Table 4 and Figs 3-5). Consequently, failure of individuals to survive for a long time in the laboratory experiment is due to their low VL when they were left on deck. It is therefore important to handle the organisms on deck quickly and safely to increase their survival when they are discarded back into the sea. During fishing operations on deck, it is recommendable to keep the organisms under a wet cover to avoid drying. Another easy method for improving the survival of discards could be a direct operating system such as a duct with water from the deck for throwing animals back into the sea.

It must be taken into account that, in addition to the unhealthy state of the invertebrates who died during the experiment, the mortality may also have been due to the captivity conditions, where no food was available and the environment was only similar to the most appropriate habitat. However, the possibility of discarded invertebrates escaping predators or obtaining food is low because of the injuries they suffer during capture (Ramsay et al. 1996, Bergmann and Moore 2001, IngólfssonIng et al. 2007). Therefore, our experimental results can be assumed as a proxy to the level of survival of discards at sea.

According to the Common Fisheries Policy and the landing obligation to prevent discarding of regulated species (MCRS, Council Reg. EC 1967/2006, Art. 15.4b), a high level of post-capture survival can be adduced by member states to include an exemption from the landing obligation in their discard management plans. Our results for the survival of *N. norvegicus* can be considered a starting point with information focused on the aim of a possible species exemption but, obviously, more studies based on larger samplings need to be carried out before this exemption can be recommended. Conversely, a second crustacean species regulated by MCRS, *Parapenaeus longirostris*, showed low survival and would not be a good candidate for exemption.

The species selected for survival estimations were the most representative of different taxonomic levels and were of ecological importance in their habitats. In view of this, the 100% survival of the crinoids *A. mediterranea* and even *L. phalangium*, whose increase in post-release mortality started at VL 3, shows that the impact of trawling on crinoid beds may be less serious than assumed until now, as most crinoid individuals would survive the encounter with trawlers and post-catch release. Furthermore, in many cases crinoid beds are essential habitats for nursery and spawning areas of some commercial species (Colloca et al. 2004). The other two echinoderms that were assessed, *O. texturata* and *E. sepositum*, gave similar results, both starting mortality at VL 3. Therefore, the results may suggest again an optimistic possibility for maintaining a good environment status and a sustainable structure on the soft-sediment habitats that form the majority of trawl fishing grounds (Piet and Hintzen 2012). However, to maintain this optimistic perspective and a good environment status on the Mediterranean fishing grounds, it is mandatory to contain the current exploitation levels, especially in other types of habitat that may be even more sensitive to trawling than crinoid beds, such as maërl and *Isidella* (Kamenos et al. 2004, Mastrototaro et al. 2017). To achieve this, fishing activity and fishing effort must be reduced, temporal and spatial closures and even permanent closed areas must be implemented, and the measures regulating the reduction of discards must be implemented (FAO 2011).

The results of the present work offer some new knowledge on the survival of discarded invertebrates that may be useful for improving ecosystem health and productivity. Nevertheless, it should be regarded as a starting point, because mortality after discards at sea depends on many factors, such as susceptibility to predation and lower competitiveness for obtaining food (Bergmann and Moore 2001, Demestre et al. 2000, Kaiser et al. 2006). Knowing levels of survival of discarded invertebrates helps to obtain a more realistic image of the state of the benthic ecosystem, and consequently of the fishing grounds. The sustainability of the exploited populations depends on the conservation of these habitats, because a large part of their life cycle takes place in them.

ACKNOWLEDGEMENTS

This study received funding from the European Commission's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 634495 for the project "Science, Technology, and Society Initiative to Minimize Unwanted Catches in European Fisheries" (MINOUW). The authors wish to thank José Guzman, Vicens Rovira, Joan Pou, Josep Maria Viñas, Maurizio Bistazzoni and Armando Costaglione, captains of the fishing vessels *Milagros I*, *Mariner*, *Punta Santa Anna*, *Estelada*, *Angela Madre* and *Real*, respectively, and all their crews, for their support in the sampling at sea. We also thank Elvira Martínez for helping on survival experiments at laboratory ZAE from the ICM.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available through the online version of this article and at the following link:
http://scimar.icm.csic.es/scimar/supplm/sm04784esm.pdf

Table S1. – Information recorded during each haul in the two study areas.

Discards regulation vs Mediterranean fisheries sustainability
M. Demestre and F. Maynou (eds)

SCIENTIA MARINA 82S1
December 2018, S1-S2, Barcelona (Spain)
ISSN-L: 0214-8358

Ecological importance of survival of unwanted invertebrates discarded in different NW Mediterranean trawl fisheries

Montserrat Demestre, Paolo Sartor, Alfredo Garcia-de-Vinuesa, Mario Sbrana, Francesc Maynou, Andrea Massaro

Supplementary material

SCI. MAR. 82S1, December 2018, S1-S2. ISSN-L 0214-8358

Table S1. – Information recorded during each haul in the two study areas. A, Catalan coast; B, Ligurian and northern Tyrrhenian seas. Hauls used for survival analysis in bold.

A	HaulNum	Date	Haulstarting time (h)	HaulDuration (min)	Avg Depth (m)	WindDir	Wind speed (km h^{-1})	WatersurfaceTemp °C	Air Temp °C	Cloudylevel (1-8)	SweptArea km^2	LATEnd	LATStart	LONGEnd	LONGStart
Catalan Coast Continental shelf	1	21/03/2016	7:05	88	61.90	N-E	9	13.8	14	1	0.0962204	41.39.551	2.49.419	41.39.815	2.55.135
	2	21/03/2016	9:09	196	92.90	N-E	12	13.8	17	1	0.2143091	41.38.281	2.55.039	41.32.096	2.55.989
	3	22/03/2016	8:05	189	86.87	N	15	13.8	14.0	3	0.1082829	41.35.967	2.46.437	41.29.749	2.38.475
	4	22/03/2016	11:10	270	85.77	N	14	13.8	19	2	0.1546898	41.28.988	2.38.230	41.38.390	2.48.060
	5	**21/04/2016**	**7:35**	**145**	**206.65**	**N**	**10**	**14**	**17**	**7**	**0.0830742**	**41.30.450**	**2.53.684**	**41.32.694**	**2.52.289**
	6	23/05/2016	7:35	206	126.55	N	7	15.9	16	1	0.1180226	41.33.425	3.03.749	41.36.895	3.10.201
	7	**15/07/2016**	**6:40**	**250**	**98.76**	**N**	**15**	**21.7**	**12**	**1**	**0.1432313**	**41.34.406**	**2.46.840**	**41.26.711**	**2.36.628**
	8	09/08/2016	7:30	125	117.04	N-E	3	22	24	1	0.1489606	41.32.783	2.58.6090	41.36.167	2.47.824
	9	09/08/2016	12:15	165	97.84	N-E	4	22	30	1	0.0515633	41.32.760	2.58.820	41.32.600	3.00.030
	10	10/08/2016	11:03	260	102.41	S-E	7	22	24	5	0.1432313	41.28.088	2.36.615	41.27.893	2.36.157
	11	11/08/2016	6:54	75	83.21	N	9	22	20	6	0.0945327	41.35.528	2.46.138	41.35.420	2.54.570
	12	30/11/2016	7:25	158	96.01	N	10	16	9	4	0.0905222	41.36.710	2.55.612	41.33.544	3.00.401
	13	30/11/2016	10:30	144	138.07	N	10	16	9	2	0.0825012	41.33.348	3.00.333	41.32.418	2.54.525
	14	30/11/2016	13:20	130	227.76	N	7	16	13	1	0.0744803	41.32.418	2.54.525	41.39.341	2.53.939
Catalan Coast Slope	**1**	**24/05/2016**	**8:30**	**350**	**315.47**	**W**	**2**	**15.9**	**20**	**1**	**0.4422270**	**41.33.016**	**3.17.870**	**41.30.396**	**3.04.074**
	2	**13/06/2016**	**8:10**	**110**	**362.10**	**E**	**2**	**20.3**	**20**	**6**	**0.1389856**	**41.29.040**	**3.04.563**	**41.27.610**	**3.11.313**
	3	14/06/2016	12:30	130	363.93	E	7	20.3	23	2	0.1642557	41.27.645	3.11.175	41.30.292	3.04.659
	4	30/06/2016	7:47	120	361.19	E	3	20.3	21	3	0.1516207	41.29.835	3.04.756	41.27.378	3.09.675
	5	30/06/2016	10:38	118	355.70	E	12	20.3	28	1	0.1490937	41.27.472	3.08.312	41.30.970	3.06.147
	6	30/06/2016	13:22	110	363.02	E	14	20.3	28	1	0.1389856	41.30.355	3.04.869	41.27.147	3.08.237
	7	19/09/2016	8:20	145	358.44	N	7	22.5	24	1	0.1832083	41.29.520	3.04.975	41.28.964	3.15.186
	8	20/09/2016	7:42	188	320.04	N	5	22.5	23	8	0.2375391	41.30.861	3.06.383	41.32.686	3.16.923
	9	04/10/2016	8:57	358	342.90	N-E	7	22.6	20	4	0.4523351	41.34.274	3.17.754	41.29.628	3.04.433

B	HaulNum	Date	Haulstartingtime (h)	Haul Time (min)	AVG Depth (m)	Winddir	Wind-speed (km h^{-1})	Bottom T °C	Watersurface T °C	Air T °C	lightlevels (W/m^2)	SweptArea (km^2)	LATend	LATstart	LONGend	LONGstart
Thyrrenian Continental Shelf	1	30/11/2016	13.45	90.00	112.00	NE	10.5	14.89	17.45	12.0	300.0	0.19265	42 14 353	42 15 843	11 20 701	11 14 209
	2	**30/11/2016**	**16.00**	**90.00**	**97.30**	**S**	**1.8**	**15.60**	**17.30**	**12.0**	**50.0**	**0.20658**	**42 18 533**	**42 15 531**	**11 14 321**	**11 19 519**
	3	**01/12/2016**	**13.25**	**95.00**	**112.00**	**NE**	**6.0**	**14.81**	**17.40**	**12.0**	**100.0**	**0.19942**	**42 14 479**	**42 15 580**	**11 21 145**	**11 14 680**
	4	01/12/2016	15.40	70.00	101.00	E	5.5	14.93	17.40	12.0	25.0	0.15438	42 17 864	42 15 876	11 14 161	11 18 576
	5	**14/12/2016**	**3.30**	**95.00**	**112.00**	**E**	**7.0**	**14.85**	**17.43**	**8.0**	**0.0**	**0.20336**	**42 14 687**	**42 17 104**	**11 19 256**	**11 12 857**
	6	**14/12/2016**	**15.15**	**105.00**	**109.00**	**S**	**6.5**	**14.71**	**16.90**	**13.0**	**0.0**	**0.23157**	**42 18 161**	**42 14 894**	**11 12 862**	**11 18 452**
	7	**15/12/2016**	**3.25**	**105.00**	**109.00**	**E**	**6.5**	**14.71**	**16.95**	**9.0**	**0.0**	**0.22476**	**42 14 455**	**42 17 771**	**11 18 051**	**11 12 094**
	8	**15/12/2016**	**15.20**	**100.00**	**105.00**	**N**	**3.6**	**14.72**	**17.00**	**14.0**	**20.0**	**0.23072**	**42 18 658**	**42 14 748**	**11 13 081**	**11 17 619**
	9	**26/01/2017**	**10.05**	**185.00**	**84.00**	**E**	**9.0**	**13.87**	**14.00**	**9.0**	**400.0**	**0.27143**	**42 21 729**	**42 29 289**	**11 06 602**	**11 02 910**
	10	**26/01/2017**	**13.44**	**204.00**	**92.00**	**S**	**5.0**	**13.84**	**14.10**	**14.0**	**300.0**	**0.31233**	**42 31 971**	**42 21 995**	**11 02 132**	**11 04 209**
	11	**26/01/2017**	**1.20**	**249.00**	**85.00**	**E**	**10.0**	**13.47**	**13.70**	**3.0**	**0.0**	**0.41849**	**42 39 602**	**42 77 830**	**10 55 204**	**11 02 800**
	12	**26/01/2017**	**6.09**	**201.00**	**84.00**	**E**	**11.0**	**13.40**	**13.95**	**1.5**	**0.0**	**0.32450**	**42 30 330**	**42 38 750**	**11 02 866**	**10 55 496**
Thyrrenian Slope	**1**	**30/11/2016**	**7.30**	**95.00**	**230.00**	**NE**	**8.0**	**14.32**	**16.40**	**4.5**	**50.0**	**0.22745**	**42 10 349**	**42 07 173**	**10 56 611**	**11 01 718**
	2	**30/11/2016**	**10.00**	**102.00**	**250.00**	**NE**	**18.0**	**14.27**	**16.47**	**8.0**	**380.0**	**0.22568**	**42 06 150**	**42 08 978**	**11 04 140**	**10 58 001**
	3	**01/12/2016**	**7.03**	**97.00**	**238.00**	**E**	**10.0**	**14.28**	**16.40**	**1.0**	**0.0**	**0.22823**	**42 10 453**	**42 06 970**	**10 56 615**	**11 02 047**
	4	01/12/2016	9.35	105.00	250.00	E	6.0	14.24	16.69	5.0	100.0	0.23469	42 06 198	42 09 113	11 03 814	10 57 476
	5	**14/12/2016**	**7.55**	**85.00**	**425.00**	**E**	**4.5**	**14.11**	**16.20**	**7.5**	**30.0**	**0.18644**	**42 02 900**	**42 01 891**	**10 52 434**	**10 58 365**
	6	**14/12/2016**	**10.30**	**90.00**	**428.00**	**E**	**1.8**	**14.10**	**16.00**	**12.5**	**160.0**	**0.19160**	**42 02 390**	**42 00 804**	**11 02 701**	**10 54 763**
	7	**15/12/2016**	**10.40**	**120.00**	**418.00**	**NE**	**5.0**	**14.11**	**16.00**	**12.0**	**380.0**	**0.25547**	**42 03 887**	**42 01 249**	**11 03 190**	**10 55 510**
	8	**15/12/2016**	**8.00**	**90.00**	**433.00**	**E**	**7.2**	**14.11**	**16.00**	**9.0**	**90.0**	**0.19356**	**42 02 814**	**42 01 933**	**10 52 497**	**10 58 840**
	9	**16/02/2017**	**6.55**	**259.00**	**420.00**	**E**	**9.5**	**14.11**	**16.10**	**3.0**	**250.0**	**0.58481**	**42 02 718**	**42 00 486**	**11 03 459**	**11 20 189**
	10	**16/02/2017**	**12.20**	**180.00**	**470.00**	**SO**	**7.2**	**14.10**	**16.0**	**15.0**	**600.0**	**0.40643**	**42 03 032**	**42 01 024**	**10 52 760**	**11 02 563**

Fisheries Research 230 (2020) 105671

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Seasonal variation in the survival of discarded *Nephrops norvegicus* in a NW Mediterranean bottom-trawl fishery

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ARTICLE INFO

Handled by Niels Madsen

Keywords:
Survival
Discards
Nephrops norvegicus
Vitality assessment
Landing obligation

ABSTRACT

The landing obligation in the revised European Union Common Fisheries Policy allows for exemptions to obligatory landing of the entire catch for species for which "high survival" of discards can be demonstrated. *Nephrops norvegicus* is an important target species in many fisheries across Europe in the Mediterranean Sea, NE Atlantic Ocean and North Sea. Historically, Mediterranean fisheries have had a high discard rate of small-sized *Nephrops*, and it is suspected that this unwanted component of the catch may have a high survival potential that is comparable to those of other EU fisheries, where survival rates of up to 0.56 have been demonstrated. However, to date, no investigations have confirmed a high discard survival rate for *Nephrops* in the Mediterranean Sea. Furthermore, the environmental, technical and biological characteristics that could affect *Nephrops* survival have been shown to be substantially different from those in the survival assessments conducted in the NE Atlantic and the North Sea. To address this knowledge gap, this study was conducted to determine the survival of *Nephrops* discarded from trawls in the Mediterranean Sea. The survival and vitality status of the discarded *Nephrops* removed from trawl catches were monitored onboard and for 14 days in the laboratory. The results showed seasonality in survival, with the highest survival rate in winter (0.74; CI: 0.7 − 0.78), lower survival in spring (0.36; CI: 0.31 − 0.41) and the lowest survival in summer (0.06; CI: 0.04 − 0.09). Survival was monitored to the asymptote in all cases, and season and vitality status were shown to have statistically significant relationships with survival.

1. Introduction

Norway lobster (*Nephrops norvegicus*) is a commercially important species that is widely distributed throughout Europe fisheries from the Mediterranean Sea and the NE Atlantic to the northern North Sea and Baltic Sea (Vasilakopoulos and Maravelias, 2016). The total discard rates in the trawl fishery targeting Mediterranean *Nephrops* can reach 30 % of the total catch, comprising a high proportion of undersized (i.e., below the minimum conservation reference size (MCRS) specimens of *Nephrops* (García -de-Vinuesa et al., 2018).

The introduction of the landing obligation (LO) in the European Union's (EU) Common Fisheries Policy aims to shift harvesting patterns in EU fisheries by reducing unwanted catches by banning discarding practices and encouraging more selective capture methods (EU Reg., 1380/, 2013). Currently, the LO applies to regulated species, that is, species for which there is a quota or MCRS; it stipulates that no unwanted catches of regulated species can be discarded: they must be landed in port and not used for human consumption ((EC) No 850/1998). However, there are situations (exemptions) in which animals may be legitimately released (discarded) from commercial fishing catches, such as those with high survival – when the survival of a species from a particular fishery has been demonstrated to be sufficiently high to justify its release (Art. 15 of EU Reg., 1380/, 2013). For the high survival exemption to be implemented, fishery-specific evidence must be presented to the European Commission, which will consider the merits of an exemption to the LO on a case-by-case basis (Rihan et al., 2019).

Technical measures have been in place for decades in an attempt to avoid catching undersized animals in the Mediterranean *Nephrops* fisheries, including an MCRS of 20 mm in carapace length (CL) and

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https://doi.org/10.1016/j.fishres.2020.105671
Received 24 January 2020; Received in revised form 29 May 2020; Accepted 13 June 2020

minimum trawl cod-end mesh sizes of 40 mm (square-mesh) or 50 mm (diamond) (Council Regulation (EC) No., 1967/, 2006; GFCM/29/2005/1). However, these control measures have not been not fully effective because substantial numbers of undersized *Nephrops* between 15 and 20 mm CL continue to be caught and discarded, contravening the LO that has been in place since 1st January 2019 (García -de-Vinuesa et al., 2018). Furthermore, the size of maturity for *Nephrops* in the Mediterranean Sea is between 30 and 36 mm in CL (Orsi Relini et al., 1998), which is much larger than the MCRS. As such, immature individuals between 20 and 30 cm are routinely caught legally, which makes this management strategy questionable.

Several studies carried out in Atlantic coastal waters have demonstrated that *Nephrops* is likely to have a high discard survival rate (Mehault et al., 2016; Merillet et al., 2018). In 2016, we carried out preliminary tests to evaluate whether *Nephrops* or *Parapenaeus longirostris* were good candidates for a study that could demonstrate a high discard survival rate in Mediterranean crustacean fisheries. It was concluded that only *Nephrops* was a good candidate, and these results were published by Demestre et al. (2018). However, these tests were limited to vitality assessment on deck, and it became evident that a more robust methodology and larger sampling efforts were needed to eventually demonstrate a high discard survival rate for *Nephrops*. To date, no investigations have confirmed a high discard survival rate for *Nephrops* in the Mediterranean Sea despite its commercial importance and the repeated realization that technical regulatory measures have proven ineffective in reducing unwanted catch.

Several factors are thought to potentially affect the survival of discarded *Nephrops*, including technical, biological and environmental characteristics (Giomi et al., 2008; ICES-WKMEDS, 2014; Mehault et al., 2016). Specifically, *Nephrops* survival varied seasonally in assessments conducted in the Atlantic (Castro et al., 2003; Albalat et al., 2010), and this may be related to biological factors such as the period of maturation and reproduction (Orsi Relini et al., 1998). Survival may also be affected by handling practices on deck (Bergmann et al., 2001; Macbeth et al., 2006) and the duration of air exposure (Davis and Olla, 2002: Broadhurst et al., 2006; Benoît et al., 2010, 2012). Rapid and abrupt changes in salinity and temperature have also been shown to negatively affect the survival of *Nephrops* (Harris and Ulmenstrand, 2004) and other crustaceans (Giomi et al., 2008).

One of the main differences between the Atlantic and Mediterranean *Nephrops* fisheries is the depth of the fishing grounds. In the North Sea and in areas close to the Iberian Peninsula, such as the northern Bay of Biscay, *Nephrops* are fished from 50 to 80 m (Ungfors et al., 2013), whereas in the western Mediterranean Sea, *Nephrops* populations are mainly located in deep water on the continental slope from 300 to 600 m (Maynou and Sardà, 1997; Maynou et al., 1998; Abello et al., 2002). This depth difference has important implications for several aspects related to the survival of discarded *Nephrops* catches. At a technical level, deep water fishing in the Mediterranean generally entails a single 6 − 7 hour haul per day, compared to areas near Scotland where 2 hauls of 3 or 4 h are generally carried out (Johnson et al., 2013). Therefore, captured individuals are likely under stress for longer periods. The fishing depths also create a large temperature differential between the nearly constant 13 °C year-round bottom temperature in the Mediterranean deep sea (Hopkins, 1985) and the warm to hot air temperatures to which catches are exposed once hauled on deck. In summer, air temperatures higher than 30 °C are common, and surface water temperatures can be 26 °C or higher in July and August (Spanish National Meteorological Office, AEMET). Sudden seasonal changes in temperature may affect the survival of discarded animals differently in the Mediterranean and Atlantic since the temperature difference to which *Nephrops* catches are exposed in the Atlantic is generally lower.

Three methods for assessing the survival of discarded animals have been described by the ICES Workshop on Methods for Estimating Discard Survival (WKMEDS): captive observation, vitality assessments (i.e., indicators of survival potential) and tagging/biotelemetry (ICES, 2014). In isolation, each method has limitations that can restrict the usefulness of the produced survival estimates. However, when two or more of these methods are combined, there is clear potential for considerable synergistic benefits, including reduced resource requirements and improved accuracy and precision of survival estimates. (ICES, 2014; ICES CRR, 2020).

The study presented here aimed to assess the survival of discarded *Nephrops* from a Mediterranean trawl fishery on the Catalan Coast, NE Spain. It used captive observations and vitality assessments to determine the seasonal variability in survival rates as well as likely causes of mortality. The results may be used to improve the sustainable management of this fishery by better informing decisions about the most appropriate measures for promoting the survival of released *Nephrops*.

2. Material and methods

2.1. Study area and fishing characteristics

The animals included in this study were sampled from 10 hauls, which were carried out in three seasonal blocks between 2016 and 2017 (spring from 24 May to 14 June; summer from 6 to 20 September; winter from 21 December to 12 February) on the "Malica" fishing grounds, which are adjacent to Blanes on the Catalan coast (Fig. 1). Malica was chosen as the study area because it has characteristics typical of Mediterranean *Nephrops* fishing grounds with regard to both the commercial importance and discard rates of *Nephrops* (García -de-Vinuesa et al., 2018). The sampling was done onboard a commercial trawler (20.6 m length, 600 HP and 64.91 GT). The cod-end nominal mesh was 50 mm diamond. The towing speed of the trawl was between 2.3 and 2.8 knots. The tow durations of the hauls were between 127 and 376 min (Table 1), with a maximum fishing depth of 408 m. The catch weight was measured through data extrapolation of subsamples taken on board and varied, by haul, between 44.1 and 248.8 kg. The air temperature was measured onboard and ranged between 5 °C in winter and 25 °C in summer. The surface water temperature was captured from official data published by the L'Estartit weather station (operated by the Catalonia Meteorological Service) near the study area and ranged between 13 °C in winter and 24 °C in summer. The temperature of the black plastic non-slip surface where the catch was sorted was between 30 and 37 °C when measured in the summer of 2019. Additionally, more cloud cover was observed in summer than in spring and winter.

2.2. Vitality assessment

The vitality status of each sampled *Nephrops* was assessed using the categorical vitality assessment (CVA) method (ICES CRR, 2020) and to avoid stressing the specimens, the evaluations were carried out as quickly as possible. This assessment method used both behavioural indicators and the presence of injuries to determine the vitality status of each animal with respect to one of four categories: 1 (excellent), 2 (good), 3 (poor) or 4 (dying or dead) (Table 2). In the event of a contradiction between the behaviour and injuries, the most negative assessment prevailed.

2.3. Sampling and survival experiment

To determine the seasonal variation in survival, a total of 10 replicate treatment hauls were carried out: 4 replicates in winter, 3 in spring and 3 in summer. A total of 1100 discarded *Nephrops* (< 27 mm CL) were sampled from the catch and were briefly held aboard the fishing vessel before transfer to a shore-based aquarium for monitoring, including a 2 − 3 hour transit time to port. During the 2-week monitoring period, a total of 13 CVAs were carried out ($T0_{...}T12$), either onboard the vessel, following transit or during captivity in the land-based aquaria (Table 3). Individuals classified in the excellent vitality

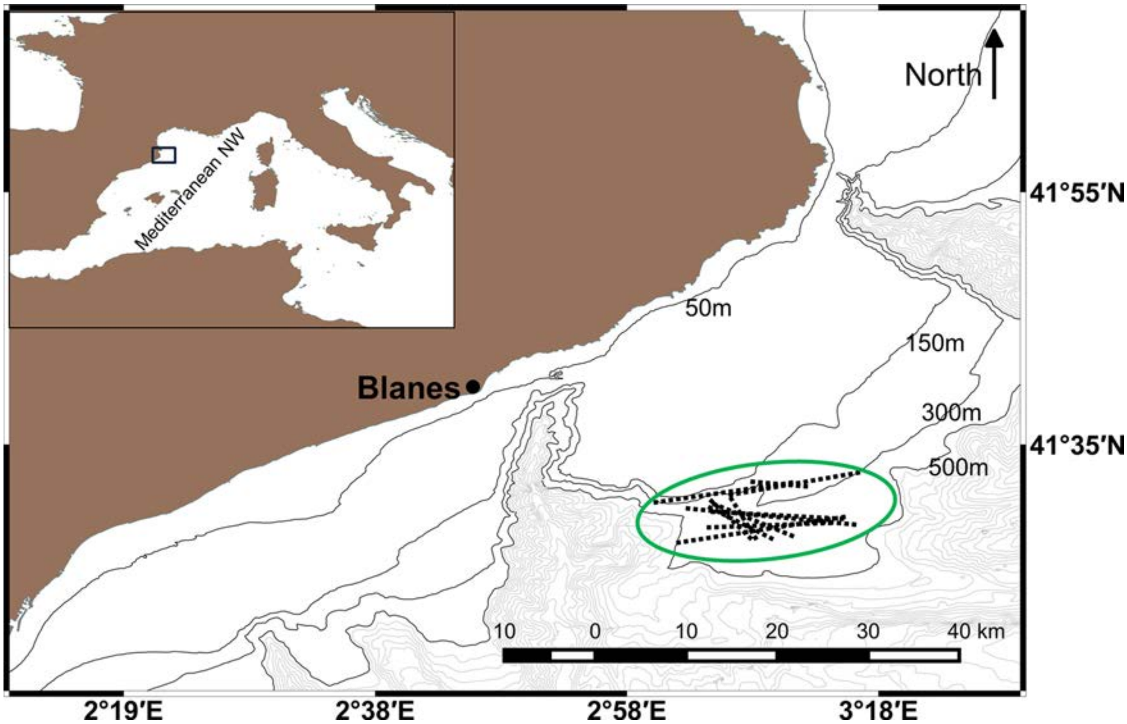

Fig. 1. Catalan Coast study area and haul locations: the "Malica" fishing grounds are shown by a ellipse adjacent to the port of Blanes, and the 10 selected hauls for the study are indicated by dashed black lines (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 1
Characteristics of each haul used for the captivity experiment: Rep ID indicates the experiment replicas in chronological order taking into account the seasons (Spr (spring), Sum (summer), Win (winter)), sample size (n), cloudiness from 1 (no clouds) to 8 (totally cloudy) (Cld (1-8)), air temperature (AT), surface water temperature (WT), haul depth (Dph), haul duration (HT) and catch weight (CW).

Rep ID	n	Cld (1 – 8)	AT (°C)	WT (°C)	Dph (m)	HT (min)	CW (kg)
Spr1	141	1	20	16	311	350	248.8
Spr2	87	1	18	20	362	210	158.5
Spr3	111	2	23	21	364	132	106
Sum1	112	3	22	23	320	376	100.9
Sum2	100	7	25	23	307	127	44.1
Sum3	101	8	23	24	320	188	86.9
Win1	109	1	7	14	275	180	91.5
Win2	108	1	12	13	309	120	112.6
Win3	115	2	7	15	408	315	180
Win4	116	1	5	15	247	345	118.7

category (Table 2) at time T_0 were taken as pseudo-controls for each haul, as per WKMEDS guidelines (ICES CRR, 2020).

2.3.1. On-board

After hauling in the net, the catch was deposited onboard on a non-slip black plastic surface, which followed the standard catch handling and sorting process of the vessel's crew. Immediately after this, *Nephrops* specimens that had been separated from the commercial fraction and were to be discarded were randomly sampled and transferred into one rectangular plastic holding tank containing surface sea water, which was renewed intermittently (Fig. 2). No more than 30 min after the catch was brought onboard, the initial CVA (T_0) was conducted, and the animals were segregated according to their vitality status (Table 2) into one of four separate white plastic containers (50 L each). The initial sample size was limited to ∼100 individuals to avoid overcrowding the specimens in any one of the four holding containers (for a maximum of 40 animals per container). The white plastic containers were supplied with running surface sea water and 5 Dajana oxygen-producing tablets per hour to prevent hypoxia. In addition, to controlling the water temperature in the containers during the warmer seasons (spring and summer), the containers were placed on ice packs during transit to the port and then transported to the laboratory in an air-conditioned vehicle (18 °C). It took a maximum of four hours to transfer the specimens back to the shore-based aquaria (i.e., a maximum of 3 h transit to the port, and 1 h from the port to the laboratory).

2.3.2. Transfer

The specimens, which were transported in the white plastic containers, were transferred as quickly as possible to the experimental aquarium facilities at the Institute of Marine Science (ICM) in Barcelona. The first hours of the assessment were the most critical period for survival, so to achieve better outcomes, an additional vitality assessment was performed when the animals were transferred into the aquaria (T1). At this moment, the CL of the largest individuals was

Table 2
Criteria for the Categorical Vitality Assessment (CVA) for *Nephrops norvegicus* in a western Mediterranean trawl fishery.

Vitality status	Code	Behavioural	Injuries
Excellent	1	Spasmodic body movements, aggressive posture	No external injury
Good	2	Continuous body movements, responds to contact	Superficial injury or loss of some pereiopods
Poor	3	Weak body movements, can move antennas, pereiopods or maxillipeds	Loss of some chelipeds or cuts
Dying or dead	4	No movement, does not respond to repeated contact	Deep cuts, crushed or punctured carapace

Table 3
Location and timing of vitality status assessments from the beginning of the experiment (T0 = 0.5 h) to the end (T12 = 2 weeks).

Places/vitality assesment in time	T0 0.5h	T1 4h	T2 16h	T3 28h	T4 40h	T5 52h	T6 64h	T7 76h	T8 88h	T9 94h	T10 1 week	T11 1.5 week	T12 2 week
On-board	x												
Transfer		x											
Aquaria (ICM)			x	x	x	x	x	x	x	x	x	x	x

Fig. 2. *Nephrops norvegicus* in the catch (left) and white plastic containers filled with surface seawater into which the samples were transferred (right).

measured to assess the maximum size of the discards. Here, individuals were again segregated into separate sections in the aquarium tanks according to their vitality status, and animals in state 4 (dead or moribund) were removed.

2.3.3. In the aquarium (ICM laboratory)

This phase was conducted in the experimental tanks at ICM. Eight further assessments (T2…T9) were conducted in the first 94 h of the observation period, with one assessment every 12 h. Later, three further assessments were made 1 week, 1.5 weeks and 2 weeks after the start of the experiment (T10, T11 and T12).

Each aquarium was partitioned into three sections, with one for each state of vitality (i.e., 1, 2 and 3). Each section had dimensions of 80 cm in length, 45 cm in width and 25 cm in depth and a maximum of 20 specimens per section to avoid overcrowding. When there was a change in the state of vitality in a specimen, it was isolated into another reserved aquarium with the same characteristics as previously described to avoid confusing it with other specimens.

To simulate natural conditions, each aquarium had an open-circuit seawater system; a water temperature between 13 and 14 °C; a photoperiod adapted to the natural light cycle; a black canvas to dim the light; periodic controls of salinity, nitrates, nitrites and silicates; and bricks and rocks to provide artificial shelter and free movements within all sections. The specimens were not fed during the assessment as in the other works (Mehault et al., 2016; Merillet et al., 2018) because *Nephrops* can naturally survive long periods without eating.

2.4. Data analysis

The vitality at the initial time (T0) per season was explored by calculating the percentages of individuals in each vitality state.

2.4.1. Kaplan-Meier

Kaplan-Meier (KM) analysis (Kaplan and Meier, 1958) was used to describe survivorship over time (with a 95 % confidence interval) for the pooled season data, pooled CVA data, replicates and pseudo-controls. To study the possible significant differences among the seasons and vitality statuses over time, a log-rank test was conducted (see below). These analyses were conducted using the “survival” and “survminer” packages in R 3.3.1 (R Development Core Team, 2016).

2.4.2. Parametric survival modelling

The generalized parametric survival model proposed by Benoît et al. (2015) was fitted to each replicate experiment in each season to estimate the survival rate at the asymptote, as per WKMEDS guidelines (ICES CRR, 2020). The time to reach the asymptote can also be estimated from this model to determine whether the monitoring period was sufficient to allow all treatment-related mortality to be expressed.

This approach models the survivorship of *Nephrops* over time based on the mortality and censoring times observed in the experiment. The model was written as follows:

$$S(\mathrm{t}) = \tau\bullet(\pi\exp[-(\alpha t)^{\gamma}] + (1-\pi))$$

where $S(t)$ is the survivorship at time t, α and γ are parameters of a Weibull survival distribution that describes the mortality of *Nephrops* as a result of the treatment (i.e., capture, transfer and captivity in aquaria), τ is the initial survival rate and π describes an asymptote in the discard mortality following the treatment (for a derivation, see Benoît et al., 2015). In this model, α, γ, π, and τ are all estimated parameters. From these parameters, one can separately estimate the initial capture and handling mortality rate, $1-\tau$, and the post-transfer mortality rate (i.e., in captivity), $\tau\pi$; thus, from these metrics, the total treatment mortality rate is $1-\tau+\tau\pi$. One can also estimate the time at which total treatment mortality has approximately reached its asymptote (i.e., within 99.9 %) as follows:

$$t_{asymptote} = \alpha^{-1}\log(1000)^{1/\gamma}$$

This variable was estimated for each replicate to confirm that all discard-related mortality had occurred by the end of the monitoring period.

The survival model was fitted to the data using maximum likelihood. The fit suitability was assessed by comparing the model predictions and non-parametric Kaplan-Meier estimates of survivorship.

2.4.3. Factors of survival

After confirming that mortality had reached an asymptote in all treatments by the end of the monitoring period (see Results), the relationship between the survival of *Nephrops,* season and vitality status

Table 4
Results of the survival rates (S.rate) together with their respective pseudo-controls and 95 % confidence intervals (C.I.) for each replicate.

Rep ID	S. rate	C.I.	n	Control S. rate	Control C.I.	Control n
Spr1	0.23	0.17 – 0.32	141	0.67	0.50 – 0.89	24
Spr2	0.51	0.41 – 0.62	87	0.91	0.79 – 1	21
Spr3	0.40	0.32 – 0.50	111	0.83	0.69 – 1	23
Sum1	0	–	112	0	–	4
Sum2	0.11	0.06 – 0.19	100	0.28	0.13 – 0.59	18
Sum3	0.07	0.03 – 0.14	101	0.50	0.23 – 1	6
Win1	0.73	0.65 – 0.81	109	0.91	0.81 – 1	32
Win2	0.69	0.60 – 0.78	108	0.85	0.74 – 0.98	34
Win3	0.70	0.62 – 0.79	115	0.94	0.87 – 1	36
Win4	0.85	0.78 – 0.91	116	1	–	35

(at T0) was investigated using a GLM with a binomial distribution and logit link function fitted to the overall survival data (i.e., after 14 days (336 h) of monitoring). To define survival after 14 days as the dependent variable, the *Nephrops* specimens with vitality 1, 2 and 3 were assigned codes of 1 (alive), while those in state 4 were assigned codes of 0 (dead). The best model was selected with a stepwise procedure based on the minimization of the Akaike information criterion (AIC), and the variance explained by the model was estimated using Nagelkerke's pseudo R^2 (Nagelkerke, 1991).

3. Results

3.1. Survival and vitality analysis

The mean overall survival at day 14 was 0.43 (95 % confidence interval, CI: 0.40 – 0.46). There was substantial variability between replicates (Table 4), with the highest survival in trial "Win4″ (Table 1) with 0.85 (CI: 0.78 – 0.91). The pseudo-controls (animals with vitality status: 1) typically had high survival rates between 0.67 and 1, except in the summer, which had survival rates of 0.5 or less.

The mean survival at day 14 showed significant seasonal variation: that in winter was 0.74 (CI: 0.67 – 0.78); in spring, 0.36 (CI: 0.31 – 0.41); and in summer, 0.06 (CI: 0.04 – 0.09) (Fig. 3). There were also significant differences in mean survival over time between vitality statuses (at T0), with the highest survival for *Nephrops* that were initially in excellent (1) condition, followed by those in good (2) and poor (3) conditions and ultimately those that were dying or dead (4) (Fig. 4). The highest mean survival (at day 14) was for those that were initially in the excellent (1) state, with 0.81 (CI: 0.76 – 0.86), while the lowest survival was observed in dead and dying *Nephrops* (vitality status 4), with 0.07 (CI: 0.04 – 0.11).

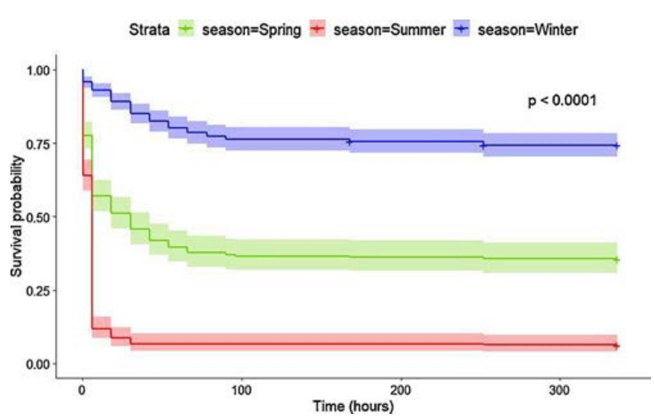

Fig. 3. Kaplan-Meier survival curves (with 95 % confidence intervals) for *Nephrops norvegicus* caught in demersal trawls in different seasons: spring (green), summer (red) and winter (blue); data from different trials/replicates were pooled within seasons.

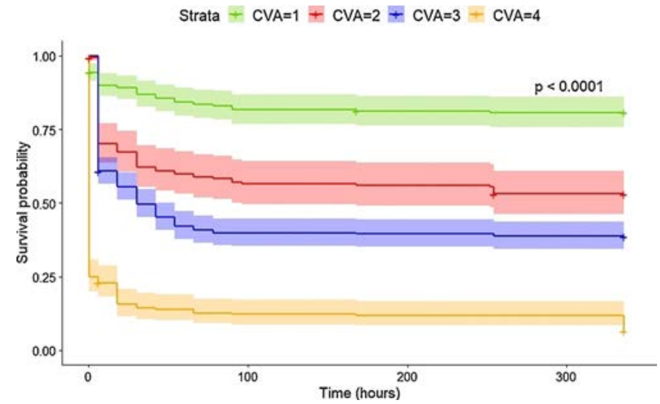

Fig. 4. Kaplan-Meier survival curves (with 95 % confidence intervals) for *Nephrops norvegicus* with respect to vitality (CVA category at t_0): excellent (1) (green), good (2) (red), poor (3) (blue) and dead or dying (4) (yellow); data were pooled across replicates/trials and seasons.

Table 5
Percentage of *Nephrops* individuals at each state of vitality per season at the beginning of the experiment (T0).

Season/CVA	1 (% excellent)	2 (% good)	3 (% poor)	4 (% dying or dead)
Spring	20.6	17.3	36.9	25.3
Summer	9.2	11.4	41.8	37.6
Winter	30.6	19.4	42.9	7.2

The results of the vitality status analysis at T0 by season showed higher percentages of animals in excellent and good conditions in winter, which decreased in spring and was the lowest in summer (Table 5). In addition, the percentage of dead or dying individuals at the initial time (T0) was lower during winter and increased in spring until reaching the highest percentage in summer.

3.2. Parametric survival modelling

The predicted survivorship functions from the parametric survival model followed the Kaplan-Meier estimates very well (Fig. 5). Estimates of $t_{asymptote}$ from the model were within the range of those during the monitoring periods for all experimental trials (Table 6).

The estimated initial mortality (0 h, $1 - \tau$) was the highest and most variable for the spring and summer experimental trials, ranging from 0.18 to 0.60, except for trial "Spr2″, which had no initial mortality (Fig. 6). In contrast, the estimated initial mortality was substantially lower in the winter, ranging between 0.04 and 0.06.

The estimated total discard mortality (at day 14) based on the parametric model was very similar to the Kaplan-Meier survival results (Table 4). The greatest mortality was in the summer experiment and ranged from 0.9 to 1.0 (Fig. 6). The uncertainty for the estimate for trial "Sum1″ was elevated because all individuals died, resulting in uncertainty in the survival asymptote parameter π. Estimates for π for spring were somewhat lower, ranging from 0.49 to 0.77, while estimates for winter were by far the lowest, ranging from 0.16 to 0.32. The confidence intervals for those estimates did not overlap those for the trials in other seasons.

3.3. Factors of survival

The deviance explained in the GLM model of survival (at day 14) was 39.79 %. Survival differed significantly between seasons, as did the vitality status (Table 7). The parameter estimates (Table 7) confirmed that survival was higher in winter and lower in summer in comparison to in spring (baseline). Moreover, the survival for vitality statuses 2, 3 and 4 was consecutively lower than that for state 1 (baseline). A

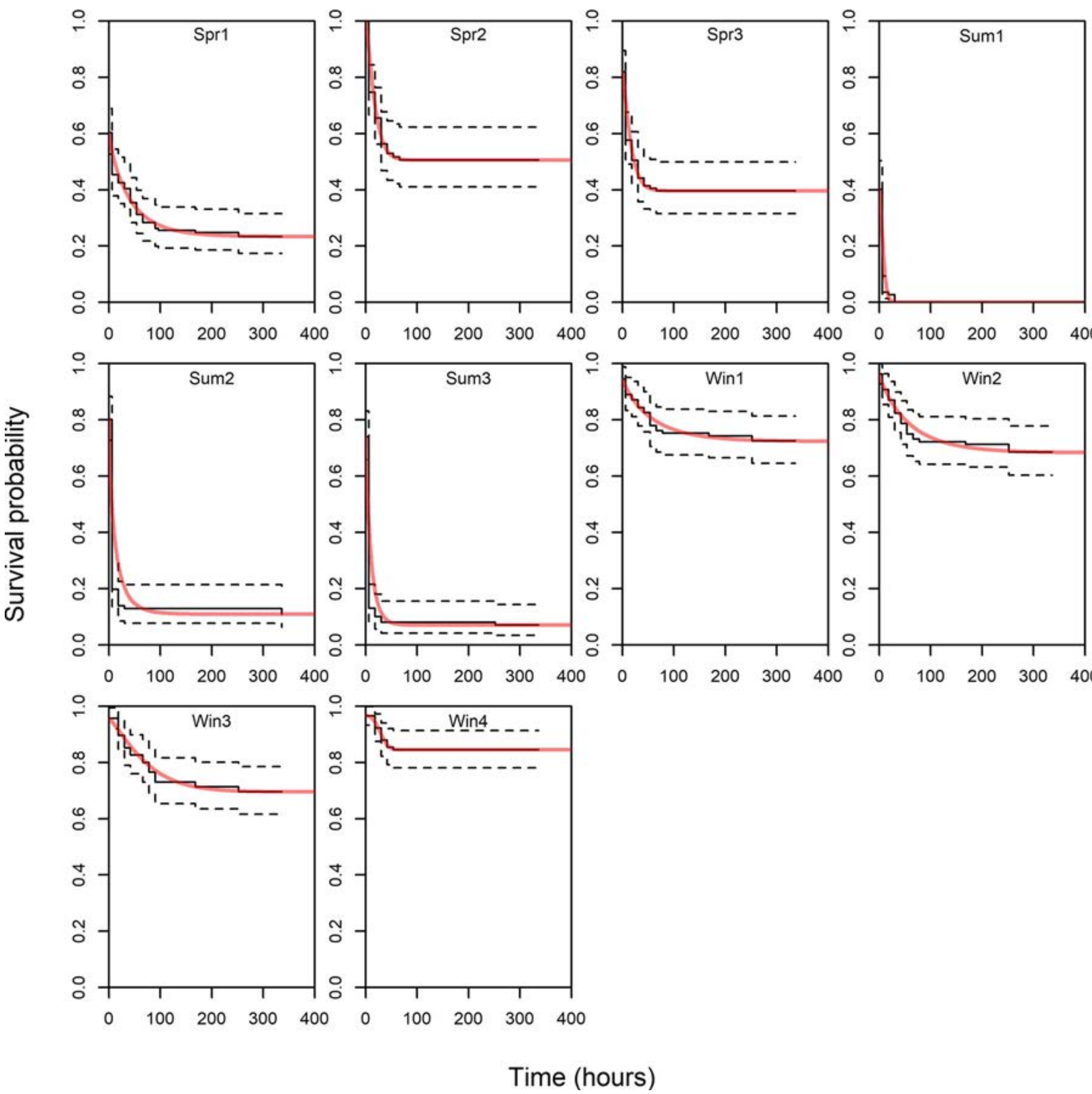

Fig. 5. Survivorship functions for *Nephrops norvegicus* sorted chronologically from left to right from spring to winter in the 10 experimental trials based on non-parametric Kaplan-Meier estimates (solid line; 95 % confidence interval, dashed line) and predictions from the parametric survival model (red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 6
Estimates of $t_{asymptote}$ from the parametric model for each replicate (Rep ID).

Season	Rep ID	$t_{asymptote}$
Spring	SPR1	227.4
	SPR2	64.1
	SPR3	60.9
Summer	SUM1	23.8
	SUM2	93.5
	SUM3	54.3
Winter	WIN1	307.1
	WIN2	314.0
	WIN3	261.6
	WIN4	58.4

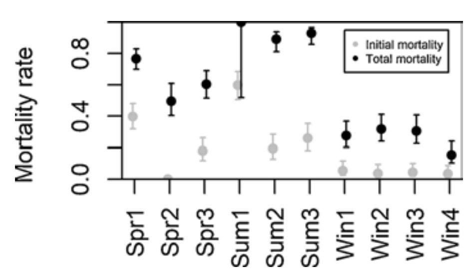

Fig. 6. Estimates (with 95 % confidence intervals) of the initial (grey) and total (black) mortality for each trial. Each trial is numbered sequentially within each season: spring (Spr), summer (Sum) and winter (Win).

significant interaction between season and vitality resulted from the survival patterns for *Nephrops* with vitality status 3 in winter.

4. Discussion

This study has for the first time provided empirical evidence for the survival of discarded *Nephrops* removed from the catch of a commercial trawl in the Mediterranean Sea. The overall mean survival of 0.43 (CI: 0.40 − 0.46) was comparable to the mean survival rates of ∼0.5 observed for *Nephrops* sampled from trawl catches in the Atlantic at comparable latitudes (e.g., Mehault et al., 2016; Merillet et al., 2018). All of these survival assessments, including that in the present study, used similar methods to determine post-capture and handling mortality,

Table 7
GLM model of survival at day 14 (336 h), with significance Pr (> | z |) where significant values are shown in bold font and standard error (Std.error), the value of the Z statistic and the estimate are shown for each parameter. The proportions of deviance explained by the increasingly more complex models were: 27.13 % (season only, AIC:1100.1), 39.16 % (season and vitality status, AIC: 935.58), 39.79 % (season and vitality status with interaction AIC: 928.01).

Time (14 days)	Estimate	Std.error	Z value	Pr(> |z|)
Intercept	1.35	0.30	4.50	**6.76E-06**
Factor(Season)Summer	−2.65	0.55	−4.82	**1.43E-06**
Factor(Season)Winter	1.09	0.43	2.51	**0.01**
factor(vitality)2	−1.61	0.40	−3.97	**7.68E-05**
factor(vitality)3	−2.02	0.36	−5.65	**1.65E-08**
factor(vitality)4	−4.81	0.66	−7.30	**2.97E-13**
Factor(Season)Summer:factor(vitality)2	1.05	0.78	1.35	0.18
Factor(Season)Winter:factor(vitality)2	0.31	0.57	0.55	0.58
Factor(Season)Summer:factor(vitality)3	0.30	0.72	0.41	0.68
Factor(Season)Winter:factor(vitality)3	0.23	0.50	0.45	0.65
Factor(Season)Summer:factor(vitality)4	1.33	1.29	1.04	0.30
Factor(Season)Winter:factor(vitality)4	1.99	0.81	2.44	**0.01**

namely, captive observation (ICES CRR, 2020).

Captive observation assesses the effects of a treatment by monitoring specimens in a suitable holding facility for a sufficient period for any resultant mortality to be expressed. Containment facilities and conditions can influence the survival of marine animals in captive observation studies (ICES WKMEDS, 2014). In previous studies, separate boxes and/or cells have been used to house individual *Nephrops* due to their cannibalistic behaviour (Sarda and Valladares, 1990). While this avoids cannibalism, it can restrict freedom of movement, which could negatively impact welfare and therefore survival. Our approach provided freedom of movement and places to hide, which better replicated conditions experienced by *Nephrops* when they are returned to their natural habitat.

To demonstrate that captivity itself has not contributed to the observed mortality, it is recommended that suitable captivity control be employed (ICES CRR, 2020). In other survival assessments of *Nephrops* (e.g., Campos et al., 2015; Merillet et al., 2018), control animals were captured using traps or short duration trawl hauls to try to obtain *Nephrops* in excellent condition. However, traps tend to select larger *Nephrops* that are not representative of discards from the trawl fishery (García -de-Vinuesa et al., 2018), while short trawl haul control groups can have survival rates that are only marginally higher than those of the treatment groups (Merillet et al., 2018). In our study, we selected individuals identified by the CVA as having vitality status 1 (excellent) as the pseudo-controls (as suggested by ICES CRR, 2020). This provided us with a subset of *Nephrops* with an appropriate size range and no notable injuries. This method works on the premise that if the pseudo-control survival is close to 1.0, then the handling and captivity that the animals are subjected to after sampling has not been detrimental to them and so is less likely to have affected the mortality observed in other specimens (ICES CRR, 2020). Conversely, if the pseudo-control survival is substantially less than 1.0, this does not conclusively infer that there was a captivity effect, but it does reduce our confidence that the observed survival in the treatments was not biased (underestimated) (ICES CRR, 2020). In general, the pseudo-control survival was high, with a mean value of 0.81 (CI: 0.76 − 0.86). However, summer was an exception, with pseudo-control survival of between 0 and 0.5. In addition, during the summer, the number of control animals was the lowest in the study, which could lead to less precise estimation of its survival. As already demonstrated in other studies (e.g., Giomi et al., 2008), we theorized that the temperature changes between the normal, stable habitat of *Nephrops* on the seabed (~13 °C) and the higher temperatures at the water surface (~24 °C), in the air (~25 °C) and on the catch-sorting mat (30 − 37 °C) induced thermal shock, which led to high mortality during the first hours of experimentation (T0-T1) on animals that previously seemed to be in an excellent state of vitality.

Refrigeration during the transfer of individuals may also not have been sufficient to achieve an appropriate water temperature (~13 °C), and future studies should employ water cooling systems during the transfer, as has already been tested in another *Nephrops* survival study (Merillet et al., 2018). Water temperatures above 13 °C during transfer could have resulted in the underestimation of survival rates during warmer periods. However, this possible underestimation does not contradict the seasonal effects on *Nephrops* survival because the CVA carried out at the beginning of the experiment (T0) was not subject to this potential experimental bias. Moreover, the initial mortality (at T0) showed marked seasonality, with higher mortality in summer (0.26 − 0.6) than in winter (0.05 − 0.1) and high percentages of animals in excellent and good condition in winter, which decreased in spring and were the lowest in summer.

Seasonal variation in *Nephrops* survival has also been observed in the Atlantic (Castro et al., 2003; Lund et al., 2009; Merillet et al., 2018), although those specimens showed greater survival during the summer. In our study, the air temperature reached 25 °C. This temperature was higher than those in other studies carried out in the Atlantic Ocean, where the temperature in summer was approximately 19.4 °C (Merillet et al., 2018). In addition, in the Mediterranean during late spring and summer (i.e., between May and September) large *Nephrops* moult prior to reproduction (Sarda and Valladares, 1990) and ovary maturation and brooding occurs in female *Nephrops* (Orsi Relini et al., 1998). This could make them more vulnerable to injury during trawling, and the reduced metabolic capacity may reduce the animal's ability to cope with the stresses of capture and handling. Thus, it would be inappropriate to discard *Nephrops* during this period because it will result in low survival. The potential for sex-biased survival should be further investigated in *Nephrops* and other crustaceans.

Another challenge faced by all captive observation survival assessments was ensuring that the monitoring period had sufficient resolution and was long enough to observe all treatment-related mortality. In this study, most mortality was observed during the first 72 h post-treatment, while we monitored mortality every 12 h up to 96 h and then at a coarser interval until 14 days. Furthermore, the survival functions in all replicates were shown to have reached asymptote within the 14-day (336 h) monitoring period.

This study provided a systematic definition of vitality status for *Nephrops*, which is the ICES recommendation for survival assessments (ICES, 2014). The GLM analysis showed a significant relationship between vitality status and survival. In addition, a log-rank test showed consistent significant differences in survival over time between all vitality levels, where the highest survival was for the excellent state (1) and the lowest was for the dead or moribund state (4). This agreed with similar studies carried out in the Atlantic (Armstrong et al., 2016; Merillet et al., 2018) and suggested that vitality may be a useful mortality predictor for discarded *Nephrops* in the Mediterranean. However, there were some inconsistencies noted between the behavioural and injury criteria used to define the *Nephrops* vitality status. Moreover, the fact that the latter group, "dead or moribund" (vitality status 4), did not consistently have zero survival indicated that the criteria used to define this vitality status could benefit from some refinement. Future work should more thoroughly investigate the relationship between initial vitality status and survival of *Nephrops* with the aim of improving our mortality predictor for discarded *Nephrops* in the Mediterranean.

5. Conclusion

The seasonal variation in post-release mortality, which had very high values in summer, suggests that a survival exemption to allow post-release discarding in summer would be ineffective. Only seasonal fishery closure during the summer months would be appropriate to avoid producing fishing mortality on undersized *Nephrops*. Alternatively, technical improvements should be made onboard fishing boats to promote the survival of unwanted catches, such as protection from direct sunlight, refrigerated holding tanks, and white (or refrigerated) non-slip sorting tables.

CRediT authorship contribution statement

Alfredo García-De-Vinuesa: Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing. **Mike Breen:** Validation, Formal analysis, Data curation, Writing - review & editing. **Hugues P. Benoît:** Validation, Formal analysis, Data curation, Writing - review & editing. **Francesc Maynou:** Supervision, Project administration, Funding acquisition, Conceptualization, Methodology, Resources, Writing - review & editing. **Montserrat Demestre:** Supervision, Project administration, Conceptualization, Methodology, Resources, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was funded by the research project MINOUW (H2020-SFS-2014-2) of the European Commission (contract n° 634495). We also want to thank the crew of the "Mariner" trawler for the help during sampling, which was indispensable for the achievement of the objectives of this work, and the Association of Fishermen of Blanes.

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