TOWARDS THE IMPLEMENTATION OF ECOSYSTEM MANAGEMENT: A MULTI-LEVEL ASSESSMENT OF A SMALL SCALE MEDITERRANEAN MULTI-SPECIFIC FISHERY

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PhD THESIS

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GLOSSARY

ATC: Accumulated Total Catch

BARCOM: The Barcelona Convention for Protection against Pollution in the Mediterranean Sea

BERN: The Bern Convention

CA: Cortical alveolar

DD: Data Deficient

EN: Endangered

EU: European Union

EW: Eviscerated body weight

F: Functional ovaries

fm: Intersexual individuals

fM: Secondary males

GE: Germinal epithelium

GLM: Generalized Linear Models

GSI: Gonadosomatic Index

GVBD: Germinal vesicle breakdown

GVM: geGrminal vesicle migration

GW: Gonad weight

IUCN: International Union for Conservation of Nature

L_{50}: Average size at sexual maturity

LC: Least Concern

LPI: Living Planet Index

LPI_{FP}: Living Planet Index for Landed Biomass

LPI_{FE}: Living Planet Index for Fishing Effort

LPI_{DEB}: Living Planet Index for Direct Economic Benefits

LRPs: Limit Reference Points

M: Primary males

MMC: Melano-macrophage centers

MCS: Mean catch size

NT: Near Threatened

NW: North-western

OM: Oocyte maturation

OSPAR: Convention for the Protection of the Marine Environment of the North-East Atlantic

PG: Primary growth

POF: Postovulatory follicle complex

Sc1: Primary spermatocytes

Sc2: Secondary spermatocytes

Sg1: Primary spermatogonial

Sg2: Secondary spermatogonial

SSF: Small-scale fisheries

St: Spermatids

STECF: Scientific, Technical and Economic Committee for Fisheries

Sz: Spermatozoa

TC: Total catch

TL: Total body length

TW: Total body weight

UNCLOS: The United Nations Convention on the Law of the Sea

Vtg1: Primary vitellogenic

Vtg2: Secondary vitellogenic

Vtg3: Tertiary vitellogenic

VU: Vulnerable

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La naturaleza está fuera de nosotros

"(...) Hace cinco siglos, cuando América fue apresada por el mercado mundial la civilización invasora confundió la ecología con la idolatría. La comunión con la naturaleza era pecado y merecía castigo. Según las crónicas de la conquista, los indios nómadas que usaban cortezas para vestirse jamás desollaban el tronco entero para no aniquilar el árbol, y los indios sedentarios plantaban cultivos diversos y con períodos de descanso, para no cansar la tierra. La civilización que venía a imponer los devastadores monocultivos de exportación, no podía entender a las culturas integradas a la naturaleza, y las confundió con la vocación demoníaca o la ignorancia.

Para la civilización que dice ser occidental y cristiana, la naturaleza era una bestia feroz que había que domar y castigar para que funcionara como una máquina, puesta a nuestro servicio desde siempre y para siempre. La naturaleza era eterna y nos debía esclavitud.

Muy recientemente nos hemos enterado que la naturaleza se cansa, como nosotros, sus hijos; y hemos sabido que, como nosotros, puede morir asesinada. Ya no se habla de someter a la naturaleza: ahora hasta sus verdugos dicen que hay que protegerla. Pero en uno u otro caso naturaleza sometida o naturaleza protegida, ella está fuera de nosotros. La civilización que confunde a los relojes con el tiempo, al crecimiento con el desarrollo y a lo grandote con la grandeza, también confunde a la naturaleza con el paisaje, mientras el mundo, laberinto sin centro, se dedica a romper su propio cielo."

Eduardo Galeano (1940 – 2015)
Tomado del libro Úselo y tírelo – 1994

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RESUMEN

Las pesquerías constituyen sistemas complejos, en los cuales el proceso de evaluación y gestión debería considerar explícitamente los atributos ecológicos, sociales y económicos del sistema. Sin embargo, una crítica común a los enfoques clásicos de la ciencia y la gestión pesquera es la prevalencia de esquemas de manejo basados en los recursos (ej. talla mínima legal de captura, cuotas de captura, rendimiento máximo sostenible). Para lograr una gestión responsable y sostenible de los recursos marinos es necesaria la interacción de pescadores, gestores y científicos. La visión multidimensional del Enfoque Ecosistémico de la Pesca (EEP) proporciona el contexto general más adecuado para la gestión de pesquerías en pequeña escala. En términos generales, el EEP se basa en la relación que existe entre la salud del ecosistema y el bienestar humano. La finalidad del EEP es planificar, desarrollar y ordenar la pesca de modo que satisfaga las múltiples necesidades de la sociedad, sin poner en riesgo la posibilidad de que las generaciones futuras se beneficien de todos los bienes y servicios que pueden obtenerse de los ecosistemas acuáticos. EL EEP promueve la participación de todos los miembros de la sociedad relacionados con la actividad pesquera, y por lo tanto el co-manejo es un elemento clave para su desarrollo. En este marco, las organizaciones más importantes del sector pesquero español son las *Cofradías*. Estas son formalmente organizaciones de derecho público que tienen establecido un ámbito territorial exclusivo de actuación en el que representan los intereses de todo el sector pesquero a la vez que actúan como órganos de consulta y colaboración de la administración. Así, las *Cofradías* gestionan la pesca local, la lonja (subasta pública de pesca) y la asistencia social al pescador. Al mismo tiempo funcionan como nexo entre el sector pesquero y los organismos de gestión nacional, regional e incluso internacional. En Catalunya, la Cofradía del puerto de Palamós es una de las más importantes de la

región del Baix Empordà y cuenta con un amplio registro histórico de la información pesquera local. Estos registros proporcionan una oportunidad única para evaluar las tendencias del esfuerzo pesquero, los desembarques totales y la dinámica temporal de las especies. Así mismo, la adquisición de información biológica de relevancia puede ser complementaria a los registros de la Cofradía. En esta tesis se evalúo como maximizar el uso de la información proveniente de la Cofradía del puerto de Palamós, a través de una visión de EEP considerando a la pesquería como una unidad socio-económica (enfoque sistémico) pero también a distintos componentes del ecosistema representando diferentes niveles de la jerarquía de la organización bilógica (comunidades y especies individuales). En un contexto sistémico, se propone el uso del Índice Planeta Vivo (LPI por su sigla en inglés) para describir la dinámica pesquera con el fin de evaluar el desempeño de la pesquería de Palamós, simultáneamente analizando el grado de cumplimiento de los objetivos de Aichi. El uso del LPI en pesquerías de pequeña escala abarca varios principios del EEP, como la descentralización, la participación de pescadores y la integración del conocimiento local. Este índice es adecuado para pesquerías multi-específicas que emplean diversas estrategias de pesca como la pesquería de pequeña escala de Palamós. Los resultados mostraron que los desembarcos en dicho puerto están representados por aproximadamente 130 especies que pueden considerarse representativas de las pesquerías de pequeña escala en el Mediterráneo Noroccidental. El 15% de las especies fueron de especial interés para la pesca, la conservación de la biodiversidad y/o para su investigación. Además se observó una tendencia decreciente en la biomasa (LPI_{FP}) de 36 grupos durante el período 2002 – 2011. Así mismos se observó una correlación negativa con el esfuerzo pesquero, pudiendo estar relacionado con los aspectos socio-económicos y ecológicos. A nivel de las comunidades biológicas, y a través de un enfoque de redes se identificaron posibles unidades de manejo en base al análisis del descarte, incorporando de esta manera las especies no objetivo. Mediante un análisis de modularidad se consideraron aspectos sociales (amplia variedad de estrategias de pesca) y componentes ecológicos (especies con diferentes atributos biológicos) de la pesquería en pequeña escala de Palamós. A partir de una matriz de presencia-ausencia de 152 eventos de pesca x 125 especies descartadas, se identificaron nueve módulos discretos. De acuerdo a las características de cada módulo, algunos podrían ser considerados como unidades de manejo no evidentes para otras herramientas de gestión. Finalmente se evaluaron los efectos de la pesca en pequeña escala sobre una especie de interés comercial, *Pagellus erythrinus*. En ese sentido, se re-evaluó el ciclo reproductivo a través de un enfoque histológico, se estimaron diversos parámetros poblacionales y se evaluó la vulnerabilidad de esta especie en relación a las actividades de la pesca a pequeña escala. Los resultados evidenciaron que en aguas del Mediterráneo Noroccidental, *P. erythrinus* es una especie hermafrodita proterogínica diandrica. Considerando esta estrategia reproductiva, los artes de pesca analizados afectaron de manera diferencial a la población. Así, mientras el palangre de fondo y las redes de enmalle capturaron principalmente machos secundarios, la sonsera afectó a los individuos de menor tamaño, posiblemente hembras y machos primarios inmaduros. Además, se encontraron evidencias de que existe un mecanismo que estimula el cambio de sexo cuando hay una disminución en el número de machos de la población. Las interacciones sociales entre los individuos parecen ser el desencadenante principal de dicho cambio. Por otro parte, la talla mínima de captura legal establecida (15 cm) es menor que la talla de madurez sexual de las hembras (L_{50}) estimado en este estudio. Con este ejemplo se pretende demostrar que la estrategia biológica de la especie es el tercer nivel jerárquico a tener en cuenta en un enfoque ecosistémico de la pesca (EEP), puesto que las especies, individualmente, responden de forma distinta al tipo de pesca y a la presión y cualquier gestión que se lleve a cabo considerando solo las especies objetivo como un conjunto fracasará.

ABSTRACT

Fisheries are complex systems, in which the process of assessment and management should explicitly consider the ecological, social and economic attributes of the system. However, a common criticism of the classical approaches to science and fisheries management is the prevalence of management schemes based resources (e.g. minimum legal catch size, catch quotas, maximum sustainable yield). For responsible and sustainable management of marine resources fishing interaction, managers and scientists is necessary. The multidimensional view of the Ecosystem Approach to Fisheries Management (EAFM) provides the most suitable for managing small-scale fisheries context. In general terms, the EAFM is based on the relationship between ecosystem health and human well being. The purpose of EAFM is to plan, develop and manage fisheries in a way that meets the multiple needs of society without compromising the ability of future generations to benefit from all goods and services that are available from the aquatic ecosystems. EAFM promotes the participation of all members of society related to fishing, and therefore the co-management is a key factor in their development. In this context, the most important organizations in the Spanish fishing sector are the Fishermen Guilds. These are formally public law organizations that have established an exclusive territorial scope in representing the interests of the whole fisheries sector while acting as organs of consultation and collaboration management. Thus, the fishermen guilds manage local fisheries, fish market (auction of fishing) and fishermen welfare. At the same time function as a link between the fishing industry and the agencies of national, regional and even international management. In Catalonia, the fishermen guild of the port of Palamós is one of the most important in the region of Baix Empordà and has ample historical record of the local fishing information. These records provide a unique opportunity to assess trends in fishing effort, the total landings

and temporal dynamics of species. Also, the acquisition of relevant biological information can be complementary to the records of the fishermen guild. This thesis was evaluated as maximize the use of information from the fishermen guild of the port of Palamós, through a vision of EAFM considering fisheries as a socio-economic unit (systemic approach) but also to different ecosystem components representing different levels of the hierarchy of the biological organization (communities and individual species). In a systemic context, use of the Living Planet Index (LPI) is proposed to describe the fishery dynamics in order to evaluate the performance of the fishery Palamós, simultaneously analyzing the degree of compliance with the objectives of Aichi target. LPI use in small-scale fisheries covers several EAFM principles such as decentralization, participation of fishermen and the integration of local knowledge. This index is suitable for multi-specific fisheries that employ different fishing strategies as small-scale fisheries of Palamós port. The results showed that the landings of SSF at the port Palamós were represented by ca. 130 species that can be considered representative of small-scale fisheries in the Mediterranean Northwest. 15% of the species were of special interest to fisheries, conservation of biodiversity and/or for research. In addition, a downward trend was observed in the biomass (LPI_{FP}) of 36 groups during the period 2002 - 2011. A negative correlation was observed with the fishing effort may be related to the socio-economic and ecological aspects. At level of biological communities and through a network approach potential management units were identified based on the analysis of by-catch, thus incorporating non-target species. Through an analysis of the modularity of by-catch from small-scale fisheries social aspects (range of fishing strategies) and ecological components (species with different biological attributes) of the fishery were considered. From a presence-absence matrix of 152 fishing events x 125 by-catch species, were identified nine discrete modules. According to the characteristics of each module at least some of these can be considered management units not evident from other techniques. Finally, the effects of SSF were evaluated on a commercial interest species, *Pagellus erythrinus*. In that sense, it re-evaluated the reproductive cycle by a histological approach, various population parameters were estimated and the vulnerability of this species in relation to the activities of SSF was evaluated. The results showed that this species has showed a diandric protogynous hermaphrodite strategy in NW Mediterranean waters. Considering this reproductive strategy, fishing gear analyzed differentially affected the population. So while bottom long-lines and gillnets mainly captured secondary males, beach seine affected the smaller individuals possibly immature females and primary males. Furthermore, evidence was found that there is a mechanism that stimulates sex change when there is a decrease in the number of males in the population. Social interactions between individuals seem to be the main trigger for such change. On the other hand, the minimum legal catch size established (15 cm) is less than the size at sexual maturity of females (L_{50}) estimated in this study. This example aims to demonstrate that the biological strategy of the species, is the third hierarchical level that must be considered in an ecosystem approach to fisheries, since species individually, respond differently to different types of fishing pressure and any management carried out considering all the species as a whole, would probably fail.

RESUM

Les pesqueres constitueixen sistemes complexos, en el quals el procés d’avaluació i gestió hauria de considerar explícitament els atributs ecològics, socials i econòmics del sistema. No obstant aixó, una crítica comuna als enfocaments clàssics de la ciència y la gestió pesquera és la prevalença d’esquemes de gestió basats en el recursos (ex. talla mínima legal de captura, quotes de captura, rendiment màxim sostenible). Per aconseguir una gestió responsable i sostenible del recursos marins és necessària la interacció de pescadors, gestors i científics. La visió multi-dimensional de l´Enfocament Ecosistémic de la Pesca (EEP) proporciona el context general més adequat per a la gestió de pesqueres a petita escala. En termes generals, l´ EEP es basa en la relació que existeix entre la salut de l’ecosistema i el benestar humà. La finalitat del EEP és planificar, desenvolupar i ordenar la pesca de manera que satisfaci les múltiples necessitats de la societat, sense posar en risc la possibilitat que les generacions futures es beneficiïn de tots els béns i serveis que poden obtenir dels ecosistemes aquàtics. El EEP promou la participació de tots els membres de la societat relacionats amb l’activitat pesquera, i per tant la cogestió és un element clau per al seu desenvolupament. En aquest marc, les organitzacions més importants del sector pesquer espanyol són les *Confraries*. Aquestes són formalment organitzacions de dret públic que tenen establert un àmbit territorial exclusiu d’actuació en el que representen els interessos de tot el sector pesquer, alhora que actuen com a òrgans de consulta i col·laboració de l’administració. Així, les Confraries gestionen la pesca local, la llotja i l’assistència social al pescador. Al mateix temps funcionen con a nexe entre el sector pesquer i els organismes de gestió nacional, regional i fins i tot internacional. A Catalunya, la Confraria del port de Palamós és una de les més importants de la regió del Baix Empordà i compta amb un ampli registre històric d’ informació pesquera local. Aquests

registres proporcionen una oportunitat única per avaluar les tendències de l'esforç pesquer, els desembarcaments totals i la dinàmica temporal de les espècies. Així mateix, l'adquisició d'informació biològica de rellevància port ser complementària als registres de la Confraria. En aquesta tesi s'avalua com maximitzar l'ús de la informació provinent de la Confraria del port de Palamós, a través d'una visió d' EEP considerant a la pesquera com una unitat socioeconòmica (enfocament sistèmic) però també considerant els diferents components de l'ecosistema, representant diferents nivells de la jerarquia de l'organització biològica (comunitats i espècies individuals). En un context sistèmic, es proposa l'ús de l'Índex Planeta Viu (LPI per les seves sigles en anglès) per descriure la dinàmica pesquera, de Palamós, simultàniament analitzant el grau d'acompliment dels objectius d'Aichi. L'ús del LPI en pesqueres de petita escala abasta diversos principis de l' EEP, com la descentralització, la participació de pescadors i la integració del coneixement local. Aquest índex, és adequat per pesqueres multi-específiques que fan servir diverses estratègies de pesca, com és el cas la pesca artesanal de Palamós. Els resultats van mostrar que els desembarcaments en aquest port estan representats per aproximadament 130 espècies, que poden considerar-se representatives de les pesqueres de petita escala a la Mediterrània Nord-occidental. El 15% de les espècies van ser d'especial interès per a la pesca, la conservació de la biodiversitat i/o per a la seva investigació. A més es va observar una tendència decreixent en la biomassa (LPI_{FP}) de 36 grups durant el període 2002 – 2011. Així mateix es va observar una correlació negativa amb l'esforç pesquer, que pot estar relacionat amb els aspectes socio-econòmics i ecològics. A nivell de comunitats biològiques, i través d'un enfocament de xarxes es van identificar possibles unitats de gestió, partint de l'anàlisi del descart, i incorporant d'aquesta manera les espècies no objectiu. L'anàlisi de la modularitat del descart provinent de la pesquera artesanal,es va considerar juntament amb aspectes socials (àmplia varietat d'estratègies de pesca) i components ecològics (espècies amb diferents atributs biològics) d'aquesta pesqueria. A partir d'una matriu de presència–absència de 152 esdeveniments de pesca x 125 espècies descartades, es van identificar nou mòduls discrets. D'acord a les característiques de cada mòdul, alguns podrien ser considerats com a unitats de gestió, fins ara no evidents com a tals eines de gestió. Finalment es van avaluar els efectes de la pesca a petita escala sobre una espècie d'interès comercial, *Pagellus erythrinus*. En aquest sentit, es va revaluar el cicle reproductiu a través d'una anàlisi histològica, es van estimar diversos paràmetres poblacionals i es va avaluar la vulnerabilitat d'aquesta espècie en relació a les activitats de la pesca artesanal. Els resultats van evidenciar que en aigües de la Mediterrània Nord-occidental, *P. erythrinus* és una espècie hermafrodita proterogínica diàndrica. Considerant aquesta estratègia reproductiva, els arts de pesca analitzats afectaven de manera diferent a la població. Així, mentre el palangre de fons i les xarxes d'enmallament van capturar principalment mascles secundaris, la sonsera afecta els individus de menor grandària, possiblement femelles i mascles primaris immadurs. A més, es van trobar evidències que hi ha un mecanisme que estimula el canvi de sexe quan hi ha una disminució en el nombre de mascles de la població. Les interaccions socials entre els individus semblen ser el desencadenant principal d'aquest canvi. D'altra banda, la talla mínima de captura legal establerta (15 cm) és menor que la talla de maduresa sexual de les femelles (L_{50}) estimat en aquest estudi. Aquest exemple pretén demostrar que l'estratègia biològica de l'espècie, és el tercer nivell jeràrquic que cal tenir present en un enfoc ecosistèmic de la pesca, atès que les espècies, individualment, responen de manera diferent als diferents tipus de pesca i a la pressió, i qualsevol gestió que es dugui a terme considerant les espècies com un conjunt, fracassarà.

CHAPTER 1

INTRODUCTION

1.1Ecosystem Approach to Fisheries Management

For many countries worldwide, fisheries imply important sources of food, livelihood, employment, and income (FAO, 2012; Martini and Lindberg, 2013). Fisheries support about 560 million people (approximately 8% of the world's population), but this figure is currently growing (Eide *et al*., 2011). Of about 34 million active fishermen, more than 90% are small-scale operators (Béné, 2006; FAO, 2010). Worldwide fisheries capture approximately 90 million tons of fish per year (FAO, 2012). Furthermore, the history of fisheries is marked by the development of more effective fishing gears, better suited technology and increasing industrialization. Thus, fishing pressure has increased in many parts of the world, and resulted in declining fish biomass (Christensen *et al*., 2014). Currently, and according to the latest statistics on global marine fisheries, approximately 29.9% of stocks are overexploited (FAO, 2012). Furthermore, impacts from fisheries on the environment have been abundantly described and reviewed (Dayton *et al.*, 1995; Goñi, 1998; Gislason, 2003). Some consequences of fishing including habitat destruction, incidental mortality of non-target species, evolutionary shifts in population demographics, and changes in the function and structure of ecosystems are being increasingly recognized (Bellido *et al*., 2011; Shester and Micheli, 2011). Up to date, fisheries management has not been very effective, often ignoring ecosystem components and interactions such as habitat, predator and prey of target species (Pikitch *et al*., 2004).

In this line, within the Strategic Plan for Biodiversity 2011–2020, target #6 of the Aichi Biodiversity Targets (ABTs) of the Convention on Biological Diversity (CBD) reads: "By 2020 all fish and invertebrate stocks and aquatic plants are managed and harvested sustainably, legally and applying ecosystem based approaches, so that overfishing is avoided, recovery plans and measures are in place for all depleted species, fisheries have no significant adverse impacts on threatened species and vulnerable ecosystems and the impacts of fisheries on stocks, species and ecosystems are within safe ecological limits.” (CBD, 2010). ABTs were conceptualized by the CBD as macro scale, global targets. These should be achieved by managing industrial fisheries but also SSFs, a significant component of global fisheries both in terms of fished biomass and socio-economic impacts (FAO, 2010). Thus, the ABTs represent a call to the international community to achieve an urgent political objective, a task that should be accomplished employing all available tools.

To reach this goal, incorporating an Ecosystem Approach to Fisheries Management (EAFM) concepts is considered essential. The EAFM is a new direction for fishery management, essentially reversing the order of management priorities in order to start with the ecosystem rather than the target species. According to Garcia et al. (2003), the overall objective of EAFM is to sustain healthy marine ecosystems and the fisheries they support. In particular, EAFM should (i) avoid the degradation of ecosystems, as measured by indicators of environmental quality and system status; (ii) minimize the risk of irreversible change to natural assemblages of species and ecosystem processes; (iii) obtain and maintain long-term socio-economic benefits without compromising the ecosystem; and (iv) generate knowledge of ecosystem processes sufficient to understand the likely consequences of human actions. The EAFM objective must be to ensure that the total biomass removed by all fisheries in an ecosystem does not exceed the total amount of system productivity, after accounting for the requirements of other ecosystem components (e.g. non-target species, protected and vulnerable species, habitat considerations, and various trophic interactions). Maintaining system characteristics within certain bounds may protect ecosystem resilience and avoid irreversible changes (Pikitch *et al*., 2004).

In addition, Garcia and Cochrane (2005) summarise the international political development of EAFM. New European Union legislation highlights the need to move towards an ecosystem-approach of marine resources in European Seas, including the Mediterranean Sea. Thus, scientific contributions to the implementation of an EFAM process have been increasing and are especially abundant in the context of conservation and fisheries (e.g. Tudela 2004; GFCM, 2005; Cochrane and de Young, 2008; Abdulla *et al*., 2009; Coll and Libralato, 2012). Accordingly, the European Union (EU) has committed itself to incorporate an ecosystem approach in its Common Fisheries Policy (CFP), a set of rules for managing European fishing fleets and for conserving fish stocks. It is agreed that EAFM depends upon suites of indicators that track the pressure exercised, the state of the ecosystem, and the socio-economic consequences of management objectives (Klein *et al*., 2010; Lassalle *et al*., 2012; Piet *et al*., 2008). However, practical implementation measures are still under preliminary development and there is a need to further develop a solid collaboration between the main stakeholders (fishermen, administration and scientists). Knowledge-based and ecosystem-model-based decision support systems are needed (Coll *et al*., 2013).

1.2 Regional Context and Definition of Small-Scale Fisheries

In Europe, Mediterranean fisheries have existed since ancient times (Lleonart and Maynou, 2003) with 50% of Europe's small-scale fisheries (SSF) taking place in the region (FAO, 2012). The Mediterranean Sea is considered a marine biodiversity hotspot, harbouring approximately 10% of world's marine species while occupying only 0.82% of the ocean surface (Bensoussan *et al*., 2010). However, European Small-Scale Fisheries (SSF) has been largely marginalised or dismissed (Pauly, 2006; de Graaf *et al*., 2011; Guyader *et al*., 2013). In many countries, this marginalisation is shown by inadequate financial, institutional and scientific support, and an underrepresentation of the concerns of people that work in this sector during policy discussions (Salas *et al*., 2007; Béné and Friend 2011; Guayader *et al*., 2013). Despite their comparatively low volume of catches and economic significance, SSF are socially and culturally important, and an integral part of the European coastal zone (Sauzade and Rousset, 2013).

The North-western Mediterranean is one of the areas where anthropogenic and environmental impacts from fishing, tourism, industry, agriculture and farming activities are more noticeable and diverse (Lloret *et al*., 2001). Generally speaking, the change in structure of the catch in the past years has been related to the overexploitation of some species and, to some extent, to the impact of some environmental factors, such as river runoff, winds mixing and water temperature (Lloret *et al*., 2001). Given the complexity and diversity of Mediterranean fisheries, the available data is probably not sufficient for regular and trustworthy assessments for most species (Lleonart, 2008). Despite the lack of stable and consistent monitoring, management policies, and the consequent absence of reliable statistics on the evolution of small-scale fishing effort, several studies have reported that SSF have declined in many Mediterranean coastal areas during recent decades (e.g. Colloca *et al*., 2004; Gómez *et al*., 2006).

As in other parts of the world, SSF in Spain have evolved in time and space from specific ecological, and changing socioeconomic and cultural contexts, which are marked by diversity rather than homogeneity (Farrugio and Le Corre, 1993; Guyader *et al*., 2013). In particular, the Catalonian coast harbours ca.30 fishing ports comprise a mosaic of heterogeneous SSF communities due to the complexity of the socio-ecological system.

According to Chuenpagdee (2012), SSF can also be defined as a high variable activity. Thus, fishing intensity and the fishing strategies show very rapid fluctuations. The strategy and gear employed fluctuate according to the ecological features of different target species, the meteorological conditions, market, and other factors. As a result, any discussion on SSF must therefore consider that there is no single definition: a so-called SSF in a given context may be large or medium-scale in another; the same applies to the term *artisanal.* This is the reason why, here is providing a brief description of the SSF of Palamós.

The socio-economical features of the fishermen community from Port of Palamós have been previously described and analysed (Alegret, 1987; Casals, 1988; Alegret and Garrido, 2004) within the context of Catalonian fisheries. This group is comprised of professional fishermen and retirees who use various techniques and traditional gears (traps, long-lines, trammel and gill nets) which are often highly selective. Most of the boats are small in size and less well equipped than the trawling fleet, although there is great variability in size, power and technological equipment. The boats can vary from about 5-6 m in length and 12-40 HP (made of wood) to about 14 to 15 m in length and 200-300 HP (made of fiberglass). All boats have VHF radio and some are equipped with probes, plotters and radars.

In general, a given boat targets several species, and can use different fishing gears and strategies throughout the year to maximize catches. The range of activity of the vessels varies with its size. Smaller vessels are restricted to shallow coastal fishing (maximum 100 m depth) and spend in average 8 hours at sea. The crew of these boats usually ranges from 1 to 3. On the other hand, large boats (with a crew of 4) can fish up to 12 miles offshore, in deeper waters. Although the latter could be hardly defined as artisanal fisheries they are still included in this group because they are run as family businesses, possess long-standing fishing traditions and use traditional fishing techniques (Casals, 1988). A final important and distinctive aspect of SSF is the physical nature of the activity. The work on board remains intense for fishermen, partly due to the small crew and the very nature of the arts and crafts.

Like many fishing communities in the Catalonian coast, fishermen of Palamós are organized into fishermen guilds, so called *Cofradías*, the most important organizations of the Catalonian fishing sector. Formally, these are public law organizations that have established an exclusive territorial scope in representing the interests of the whole industry. The fishermen guild offer various services to its members including access to local markets, and are responsible for managing the first sale of daily catches by means of an open auction (Alegret, 1989).

In Catalonia, fisheries´ management competences rely on the autonomous regional government. In this context, the figure of *Cofradías* links the fisheries sector and the administration serving as a co-management instrument (Alegret, 1999). Each *Cofradía* manage fishing activities in their territorial limits according to three types of fleet: trawling, purse-seining and small-scale. Each one sets up a timetable for port entry and exit, closed fishing periods and regulations for each particular fleet in the fishing zones hold under jurisdiction. These resolutions are proposed to the administration to become laws. Moreover, management of catch and sales, control of the first stage of commercialization (auction market) and vessel registration among other task is as well under their administration domains. Therefore, the *Cofradía* could provide data on a wide range of species, and appear to offer a valuable scientific tool for implementing an EAFM.

1.3 Towards Ecosystem Approach to Fisheries Management in the Palamós Small-Scale Fisheries.

In this context, the aim of this thesis is to analyse the small-scale fishery of Palamós incorporating principles of the ecosystem approach to fisheries management (EAFM), hoping that the results of the present work can be easily transferred to key stakeholders in order to improve the management and monitoring of the SSF. The research was developed at three different levels within the hierarchy of biological organization:

1) at a systemic level, aiming to detect socio-ecologic trends in the fishery,

2) at a community-ecosystem level, addressing the issue of by-catch in the SSF and

3) at a species-population level, focusing on the effects of the SSF in a commercially important fish species.

Based on the case study of Palamós port, this thesis provides new insights and relevant information to aid the implementation of EAFM in small-scale fisheries in the North-western Mediterranean Sea. From a systemic perspective, temporal assessments of the socio-ecological system trajectories are essential to contextualize and monitor the state of SSF. The time-series data of species landed from the fishermen guilds can be useful to estimate trends in fisheries dynamics. This information should be presented in a simple manner so that decision-makers can make a quick interpretation of the situation. The Living Planet Index (LPI) is an easy tool to interpret this kind of information and is especially well suited for operate in the science-policy interphase. EAFM depends on suites of indicators that track the pressure exercised, the state of the ecosystem, and the socio-economic consequences of management objectives. EAFM takes into account that fisheries are embedded into the environment and cannot be managed in isolation. It has to be considered as the application of sustainable development principles to the fishing sector, combining ecological sustainability, economic viability and social fairness. Therefore, LPI is proposed here for describing the performance of SSF because applies several principles of the EAFM, including decentralization, fishermen participation, and consideration of local knowledge.

However, this provides information only on the target (landed) species. Ecosystem functioning depends on a dynamic relationship within species, among species and between species within the environment. In this regard, according to EAFM, it is necessary to consider the ecosystem components and interactions as a whole. At a community-ecosystem level, in this thesis is proposed the use of the network approach to identify management units that may not be evident using other methodologies. The network approach allows defining the structure of relationships between entities (e.g. fishing events, species, etc.) within a fishery, integrating both social (e.g. a wide variety of fishing arrays) and ecological (e.g. species with different biological attributes) aspects in the analysis. In this line, the modularity is used as a basic attribute that reflects the organization of species in community structure. This methodology it's useful to evaluate the relationships among by-catch species and changes in the dynamics of an ecosystem caused by fishing. EAFM must delineate all marine habitats utilized by humans in the context of vulnerability to fishing-induced and other human impacts, identify the potential irreversibility of those impacts, and elucidate sensitive habitats for species for vital population preservation processes. Protecting essential habitats for species and other important ecosystem components from some fishing practices increases species diversity and abundance thus will be a critical element of EAFM.

Finally, to date, fishery management has often been ineffective and generally knowledge on the reproductive biology and ecology of a targeted species is not taken into account in the design and implementation of managerial actions. In this sense, at the species-population level, in this thesis is re-evaluated the reproductive cycle of a fish species of commercial interest by a histological approach and sseveral parameters related to the life-history traits of target species is estimate. This biological information is considered to evaluate the effect of the fishery on the vulnerable commercially important sea bream fish. In the context of EAFM, one of its aims is to achieve a sustainable exploitation of commercial fisheries, providing specific consideration of the interactions between fishing gears and marine ecosystems.

Thus, along this thesis, the principles of EAFM (e.g. decentralization, participation of different actors, integration of local knowledge) have been explicitly used to design and implement the research. The analyses used are based on pre-existing basic information stored in records of the fishermen guild. However, both information from onboard biological sampling and data gathered by local fishermen are also of outmost importance for this thesis, highlighting the importance of local fishermen as key stakeholders towards the real implementation of EAFM. Decisions on the spatial and temporal allocation of fishing effort, targeted species and used fishing gear involve multiple criteria that based on fishermen knowledge combines the ecological, economic, and technical dimensions. Thus, even if catch data are mainly considered as a proxy of ecological conditions, that information could be an underexploited indicator of the whole socio-ecological system. The results of this thesis confirm the necessity of incorporate EAFM in order to manage local fisheries in a responsible and sustainable manner.

1.4 Monitoring Small-Scale Fisheries (Systemic Approach)

Monitoring SSF constitutes a challenge due to limited information on the type and amount of catch, and the underlying socioeconomic and cultural characteristics. Assessing the relative sustainability of fisheries requires information on the catch and effort of fishers, the state of exploited populations, and the changes in these factors over time (Lunn and Dearden, 2006). Small-scale fisheries typically involve a wide variety of target species, gear types, landing areas, and distribution routes, making it virtually impossible to collect reliable and comprehensive statistics for the vast majority of fisheries (King and Lambeth, 2000). In this sense, Mediterranean small-scale fishing is a very variable activity. Catches are highly multi-specific and fishing intensities and strategies show very rapid fluctuations in space and time (Farrugio and Le Corre, 1993). This may constitute a serious impediment to assess the compliance level of ABT for 2020.

In consequence, and taking into account the urgent need for the development of more effective monitoring and management schemes, the Living Planet Index (LPI; see Loh *et al*., 2005), it can be useful for describing fisheries dynamics in order to contribute to the sustainable management of fishing resources. The LPI can be useful capitalizing available data helpful to track the state of SSFs, conceptualized as socio-ecological systems. The LPI usage demands no technical skills, pose no statistical assumptions often hard to accomplish (data independence, normality, homogeneity of variance, etc.) and can be presented as an easily understandable trend line analogous to such commonly used economic indicators as GDP or stock market performance indices. Finally, the LPI has been adopted by the CBD as an indicator of progress towards its 2011–2020 targets. This index was originally developed to provide the general public, scientists, and policy-makers with information on abundance trends of the world's vertebrates as a measure of the changing state of the world's biodiversity over time based on a proportional change in abundance measure across all species from year to year. The LPI is thus especially well suited for (and was designed to) operate in the science-policy interphase. Furthermore, the use of an aggregated index such as the LPI is also especially well suited to standardize the reporting of information for multispecies fisheries using a wide array of fishing strategies. This standardized information will be extremely useful to enhance management effectiveness towards political goals such as the ABT.

1.5 By-catch: Looking at Non-Target Species

Fisheries, as complex socio-ecological systems, need the interaction of fishermen, managers and scientists to achieve a responsible and sustainable management of marine resources (Hilborn, 2007; Gutierrez *et al*., 2011; Brewer and Moon, 2015). However, a common critic to the classic approaches of fisheries science and management is the prevalence of resource-based management schemes (e.g., legal-sizes, catch-quotas, Maximum Sustainable Yield) that tend to underscore the importance of the socio-ecologic environment in which fisheries operate.

In this context, by-catch is widely acknowledged as one of the most pressing issues to marine conservation and fisheries sustainability (Hall and Mainprize, 2005; Shester and Micheli, 2011; Bellido *et al*., 2011) and a source of uncertainty for fisheries scientists and decision-makers. This problem affects not only the viability of population of species occurring as by-catch, but also the entire trophic webs and habitats. Thus, by-catch and discard reduction should become a regular part of fishery management planning (e.g., Harrington *et al*., 2005). However, it is far from being an easy issue to solve, as it involves economic, legal, and biological considerations. To date, the main approaches commonly used to mitigate its negative effects include area closures (permanent or temporal) and/or fishing gear modification (e.g., larger mesh size). The latter may be easier to implement in a fishery employing only one fishing gear (e.g., trawl net, longline), but presents evident logistic problems in multi-species fisheries that employ a wide array of fishing gears. In this case, different fishing strategies may be impairing the same non-targeted species in different ways, and thus modification of several fishing gears may be needed to avoid or reduce the impact in non-targeted species. Thus, the identification of discrete management units in the by-catch based on both ecological and technological features of a fishery may be of outmost importance to inform the allocation of management efforts aiming at by-catch reduction.

To this end, the structure of relationships between entities (e.g., 59 fishing events, species, etc.) within a fishery can be studied using a network approach, thus integrating both social and ecological aspects in the analysis (Marín and Berkes, 2010; Bodin and Tengö, 2012). To date, however, the social and ecological components of fisheries management have been assessed separately. Ecologists have focused on an ecosystem-based approach, emphasizing species interactions – essentially food webs – and how the removal or addition of these interactions can push the ecosystems to tipping points (Beunen and Hagens, 2009; Blick and Burns, 2009; Leibenath, 2010; Vimal *et al*., 2012; Watts *et al*., 2011). Social scientists, in turn, have developed a sharper focus on interactions among stake holders and within the governance systems (Hasler *et al*., 2011; Parsram and McConney, 2011; Trifonova *et al*., 2014). However, is the interaction of both social (e.g., market demand, cultural issues) and ecological (e.g., fish abundance and behaviour) components that shape fisheries dynamics and fishermen behaviour (e.g., Kittinger *et al*., 2013).

In network analysis, modularity refers to the degree to which some entities in a group or module have a higher probability of mutual connection than entities in others groups (Girvan and Newman, 2002). In ecology, this metric has been used to identify biological units that reflect the common use of resources by individuals at different scales (metapopulation, metacommunity, biogeographical, etc. (Fortuna *et al*., 2009; Bellisario *et al*., 2010; Borthagaray *et al*., 2014; Carstensen *et al*., 2012).Compared to alternative approaches, modularity has the advantage that the number and size of modules is a result of the network itself, and not a priori definition made by the researcher (Newman, 2006; Carstensen and Olesen, 2009). Moreover, the modularity analysis may admit the possibility that no compartmentalization exists (Newman, 2006).

In multi-species fisheries, multivariate analysis as principal component analysis and cluster analysis has been frequently applied to identify relatively homogeneous groups in terms of catch composition, fishing area, and fishing gear used (He *et al*., 1997; Pelletier and Ferraris, 2000; Iriondo *et al*., 2010; Párraga *et al*., 2012; Ligrone *et al*., 2014; Moutupoulos *et al*., 2014). However, in those methods the number of groups is defined by the researcher based on personal expertise and knowledge of the fishery, and there is much more subjectivity in groups delimitation. Therefore, is suggesting that a modularity analysis could be especially useful to identify discrete management units within a given fishery, and very valuable in multi-species fisheries that employ a wide array of fishing gears. To the best of our knowledge, this approach has not been developed to date in fisheries science.

1.6 Species of Particular Interest: The Common Pandora Pagellus erythrinus (Linnaeus, 1758)

Effective fisheries management has always been a challenge, especially in complex multi-species, multi-gear fisheries (Staples *et al*., 2014). Traditional stock-based approaches have largely been ineffective (see eg. King, 2010; Pomeroy *et al*., 2013), with management measures often not taking other important aspects of the fisheries into account. As many fisheries have declined over the past 30 years (FAO, 2012), the need for more effective and equitable management is increasingly evident. The EAFM offers a practical and effective means to manage complex fisheries more holistically. It represents a move away from fisheries management that focuses on target species, towards systems and decision-making processes that balance environmental, human and social well-being within improved governance frameworks. However, progress in developing EAFM plans has been slow, mainly due to a lack of experience in implementing this integrated and holistic approach, as well as the lack of comprehensive information on the species.

Knowledge on the reproductive biology of a species comprises a key aspect for fisheries management. Reproductive biology largely determines the productivity and therefore populations' resilience to exploitation and other sources perturbation, both natural and anthropogenic (Morgan, 2008). Life history parameters such as size and age at maturity, spawning season and duration, sex ratio, or fecundity often vary temporarily within a population, or among populations in a meta-population, altering its productivity or reproductive potential over time (Morgan, 2008) while other aspects of fish reproductive biology such as reproductive strategies, remain more stable during evolutionary history. Furthermore, such variations may even involve changes in mortality and energy allocation between growth and reproduction (Rijnsdorp, 1990; Stearns, 1992). While these reproductive traits are often highly variable, others aspects of fish reproductive biology such as reproductive strategies, remain more stable during a species evolutionary history.

Hermaphroditism is a common reproductive strategy in diverse taxa among teleosts (Ross, 1990), being a species or population considered to exhibit functional hermaphroditism if a proportion of individuals can act, either sequentially or simultaneously, as male and/or female at some time during their lives (Sadovy and Shapiro, 1987; Sadovy and Liu, 2008). However, fish species that experience sequential hermaphroditism are distinctively vulnerable to fishing impacts because fishing mortality, when size-selective, may be affecting differentially males and females

(Huntsman and Schaaf, 1994; Alonzo and Mangel, 2004, 2005; Provost and Jensen, 2012). Even if there is a significant interest in the fishery biology of hermaphroditic species because of their economic relevance (Levin and Grimes, 2002) and the differential impacts of fishing on their populations if compared to gonochoristic species (Shepherd and Idoine, 1993; Alonzo and Mangel, 2005; Heppell *et al*., 2006), there are still large gaps in knowledge for most hermaphroditic species (Provost and Jensen, 2012).

Particularly, protogynous species require special management considerations when fishing reduces survival probability of the male fraction of the population because protogynous hermaphroditism is an important life-history pattern in many families of teleost fishes (Policansky, 1982; Sadovy and Shapiro, 1987; Ross, 1990; Shepherd *et al*., 2013) which implies a sequential reproductive function, with females dominating early life stages and later shifting to males during the individual ontogeny.

If a hermaphroditic species experiences an increasingly biased sex proportion, or maintains its optimal sex ratio advancing individuals rate of sex change, the consequences could be critical for its population dynamics (Shepherd *et al*., 2013). Under an exclusive natural mortality scenario, sex ratios of protogynous populations are expected to be biased toward females (Allsop and West, 2004). But if include fishing mortality, this ratio could even raise further (Coleman *et al*., 1996; McGovern *et al*., 1998; Armsworth, 2001), especially if fishing selectively removes males by targeting larger (older) individuals, i.e. due to gear selectivity or management regulations. Subsequently, selective removal of a particular sex or size class over many generations can have evolutionary consequences, including slower growth rates, reduced size at maturation and earlier sexual transformation (Harris and McGovern, 1997; Adams *et al*., 2000; Brulé *et al*., 2003; Heppell *et al*., 2006).

Sparidae (sea breams) is one of the most diverse families of teleosts in relation to patterns of sex allocation (Buxton and Garrat, 1990), including few species described as either protogynous, protrandrous, or gonochoric due to the variation in gonadal configurations that make diagnosis of sexual pattern particularly challenging (Erisman *et al*., 2014). Among the sea breams, the common pandora, *Pagellus erythrinus* (Linnaeus, 1758) has been shown to display diandric protogynous hermaphroditism (Larrañeta, 1964; Andaloro and Giarritta, 1985; Girardin and Quignard, 1985; Papaconstantinou *et al*., 1988; Livadas, 1989; Pajuelo *et al*., 1998; Coelho *et al*., 2010). This species occurs along the Black and Mediterranean seas and along the eastern Atlantic, from Norway to Angola (Bauchot and Hureau, 1986). The common pandora is found most often at depths from 26 to 177 m (Somarakis and Machias, 2002) and is a benthophagous feeder, preying mainly on epibenthic and infaunal organisms (Rosecchi, 1983; Benli and Kaya, 2001; Fanelli *et al*., 2010).

Common pandora is also a high-value species and constitutes an important resource for Mediterranean fisheries (FAO, 2005) being captured by gill or trammel nets, long-line, seine and trawling (Erzini *et al*., 1998; Stergiou *et al*., 2006; Gancitano *et al*., 2010). According to data provided by FAO for the Mediterranean and Black Sea (FAO, 2015; Tsikliras *et al*., 2013), landings of the commom pandora have been declining since the 90´s (see Figure 1) and there are documented events of overexploitation in several European fisheries (e.g. Coelho *et al*., 2010).

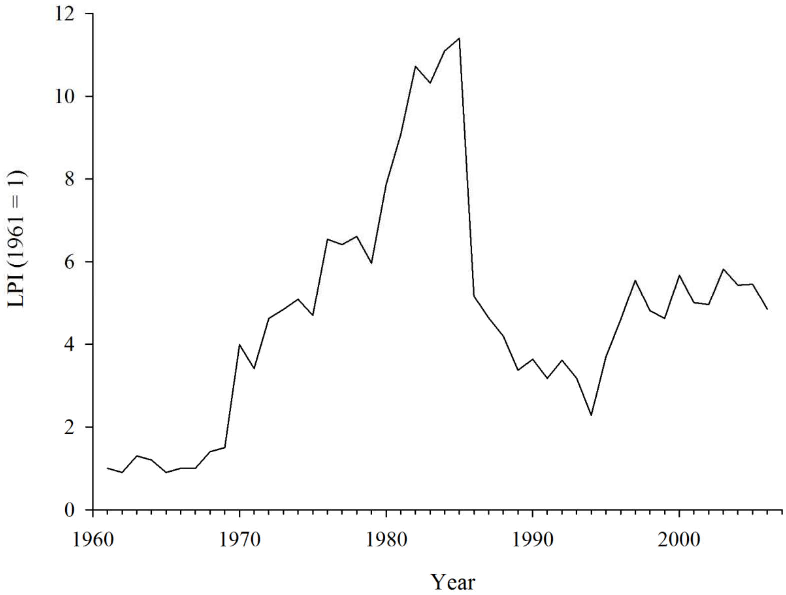


Figure 1: Living Planet Index (LPI) trajectories for total landing (LPI_{TL}) for *P. erythrinus* estimated from total catch from Mediterranean Sea 1960-2006 (Data from FAO, Global Production Statistics, Fisheries and Aquaculture Information and Statistics Service retrieved 06/02/2015).

Several studies carried out in the Mediterranean focused on the estimation of population parameters, including age, growth, reproductive aspects and other relevant features such as feeding behaviour (Ardizzone and Messina, 1983; Andaloro and Giarritta, 1985; Girardin and Quignard, 1985; Papaconstantinou *et al.*, 1988; Livadas, 1989; Mytilineou, 1989; Somarakis and Machias, 2002). In addition, fisheries-related researches on aspects of the species´ biology and exploitation impacts are also available (Santos *et al.*, 1995; Jarboui *et al.*, 1998; Ateş *et al.*, 2010; Gurbet *et al.*, 2012; Özbilgin *et al.*, 2012). However, and at least in Spain, the management of the common pandora is currently based only on legal sizes. In particular, as outlined above, this managerial scheme may not be appropriate for protogynous species such as the common pandora; knowledge on the reproductive ecology of the common pandora could better support managers in the evaluation of regulatory options.

1.7 Objectives

This thesis evaluates how to maximize the use of information coming from the fishermen guild of Palamós port, to delve the implementation of EAFM in the small-scale fisheries, considering the fishery as a socio-economic unit (systemic approach), but also to components representing different hierarchy levels of biological organization (individual species and communities) ecosystem. Likewise, the use of new methodological tools for the analysis of components of interest is proposed, based on the existing basic information in the records of the fishermen guild complemented with new information from biological sampling of the fishery. Thus, this thesis aims to 1) Evaluation to track the state of the ecosystem (trends in Fish Populations), the pressure exercised (trends in Fishing Effort), and trends related to the contribution of fisheries to broader society, whose joint analysis should improve the assessment of the socioeconomic performance of a small-scale fisheries of port of Palamós. 2) Evaluate and understand by-catch structure from small-scales fisheries of Palamós, considering some key components of the social and ecological dimension. 3) Assess the effects of small-scale fisheries on the *Pagellus erythrinus* population characteristics.

To this end, 3 specific objectives were defined:

1) Evaluate the Living Planet Index as a suitable index to standardize the reporting of information for multispecies fisheries using a wide array of fishing strategies.
2) Estimate the modularity as a network metric and characterize the observed modules.
3) Re-evaluate the reproductive cycle by a histological approach, estimate several populations' parameters and evaluate the vulnerability of this species in relation to the small-scale fisheries activities at the Palamós fishing area.

CHAPTER 2

MATERIALS AND METHODS

2.1. Study Area

The study area is located in the district of Baix Empordà in the Costa Brava (North-western Mediterranean Sea) (Figure 2). Geomorphologic features of the area include rough terrain and cliffs, with small bays along the coast, and a steep continental shelf, reaching 100 m depth at 50 m from the coast. The submarine topography of the area is also conspicuous, including features such as the Palamós Canyon. The region encompasses a high temperature-productivity gradient in the NW Mediterranean, characterized by cold, relatively eutrophic waters maintained by local upwelling. Surface seawater temperature varies between 11-12ºC and 25-26ºC during winter and summer, respectively (Bensoussan *et al*., 2010; Cebrián *et al*., 1996). These conditions are reflected in a high biological productivity and biodiversity, including habitats such as coralline outcrops, rocky bottoms and seagrass beds (Ballesteros, 2006; Alcoverro *et al.*, 1998).

2.2 Sampling Methods

The data used in this thesis come from onboard samplings, port samplings and historical daily sales records of the fishermen guilds of Palamós (Figure 3).

2.2.1 Onboard sampling of catch

From January 2010 to February 2012 a weekly onboard sampling (n=88 fishing trips) was carried out to keeping record of the species of commercial interest of small-scale fisheries in Palamós. Sampling was performed on daylight fishing trips in 8 fishing boats (total vessels 24), which were restricted to coastal zones up to 150 m depth. A monthly record of the 5 most used fishing gears in the small-scale fishery of Palamós was recorded. These fishing gears were trammel nets, gillnets, bottom long-line, beach

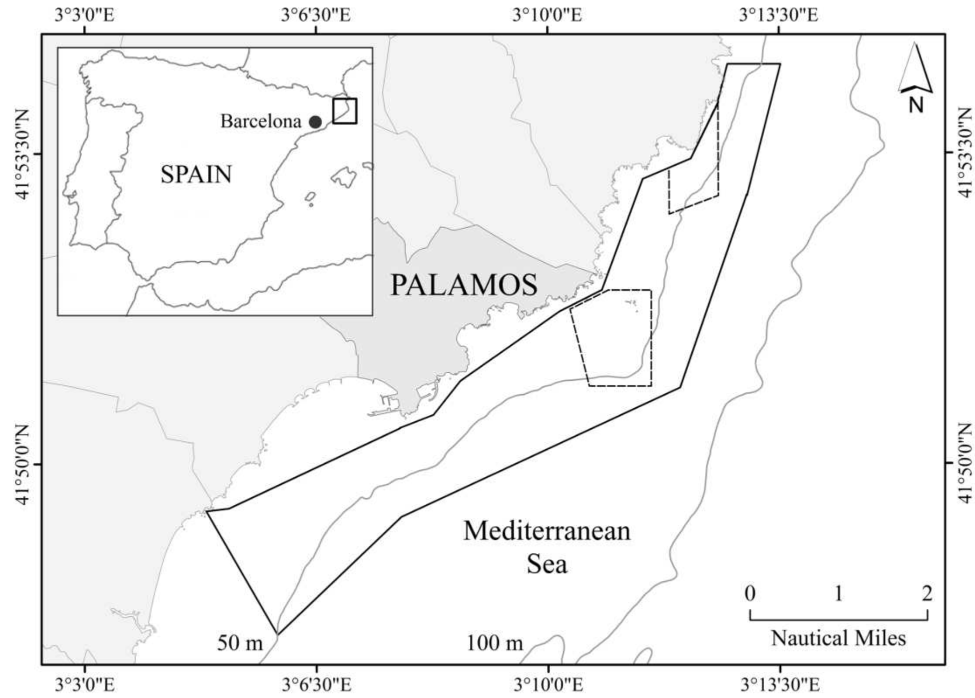


Figure 2: Study area, Port of Palamós (NW Mediterranean) area of use of small-scale coastal fishing fleet. The boundaries and two restricted areas of use to the Marine Protected Reserve proposal by the Ministry of Environment and Rural and Marine are show in the square.

1) Onboard sampling:

- catch of the species of commercial interest
- by-catch (non target species and target species)

2) Fishermen guilds:

- daily sales records

3) Sampling port:

- morphometric data and histological assessment of gonads

Figure 3: Information sources of the data used in this thesis.

seines and octopus traps (Table 1). A fishing event (FE) was defined as a fishing operation in which a given fishing gear is deployed and retrieved, and some portion of the total catch is retained by fishermen. Within each trip, the recorded information for each FE includes information on behavioural decisions of fishermen (gear type, spatial allocation of fishing effort, date, depth), and the total length (TL, ±0.1 cm) of all fishes caught to commercial interests.

Table 1: Total fishing events observed in onboard sampling to obtain total catch and by-catch composition to five gear types used in small-scale fisheries of Palamós.

Gear	Nº of fishing events	Closed season
Octopus pots	56	August - December
Trammel net	55	September – February
Bottom long-line	42	-
Gillnet	40	-
Beach seine	35	December - February
TOTAL	228	

For each fishing event, all the organisms caught were identified on board to the lowest possible taxonomic level. For each of the identified species, conservation status is indicated through international listings and/or protection agreements at European and/or local levels. Concerning the inclusion of species listed under the IUCN Red List of Endangered Species, and if of including several species under a given group (often Family), were searched for all species within the group occurring in the Palamós fisheries, and assigned the "*worse*" threat category according to the Precautionary Principle. For example, for the family Sepiidae (cuttlefish), two of the three species known from Palamós are listed as Data Deficient (DD) and the other as Least Concern (LC). In this case, LC was assigned to the whole group.

2.2.2 Onboard sampling of by-catch

The most accepted by-catch definition at the Mediterranean Region was used in this thesis, *i*.e. by-catch is considered as the incidental capture of non-target species or organisms that do not meet certain criteria (e.g., minimum size) and thus include both retained and discarded by- catch. These are not marketed, but often discarded, used as bait or for own consumption. By-catch has been recognized globally among the most important issues for fisheries management, since it is considered a waste of resources, a source of uncertainty for fisheries scientists and decision-makers, as well as a factor affecting biodiversity and community structure (Hall and Mainprozi, 2005; Shester and Micheli, 2011; Bellido *et al*., 2011). Moreover, it is far from being an easy issue to solve, as it involves economic, legal, and biological considerations.

From the onboard samplings performed to assess catch composition of this small-scale fishery (see previous section 2.2.1), by-catch species were identified onboard to the lowest possible taxonomic level for each fishing event. In the case of not being able to identify the species on board a photograph was taken or the individual were preserved in marine water and brought to the laboratory for subsequent identification. In some cases, species were grouped under a given genus or family because there was not possible to identify some decomposed individuals to species level. In each fishing event, by-catch species identity can be correlated with the ecological setting associated with a given event (bottom type, microhabitats, pelagic vs. demersales, etc).The conservation status for by-catch species was established using the same procedures as for commercial species (see section 2.2.1).

2.2.3 Daily sales records of the small-scale fisheries of Palamós

Like many fishing communities in the Catalonian coast, fishermen of Palamós are organized into fishermen guilds, so called *Cofradías*, being the most important organizations of the Catalonian fishing sector. Formally, these are public law organizations that have established an exclusive territorial scope in representing the interests of the whole industry, while acting as an organization of consultation and collaboration with management agencies. The fishermen guild offer several services to its members including access to local markets, and are responsible for managing the first sale of daily catches by means of an open auction (Alegret, 1989).

In this line, the daily sales records of the period 2002-2011 were used to assess the state of the SSF fleet. These data were analyzed in order to estimate total landings of the artisanal fishing, considering the information corresponding to "bottom long-lines" and "minor fishing gears" based on the classification of the fishermen guild of Palamós. Once the selected boats were identified (n=77), several aspects were considered to characterize the SSF fleet: period of fishing activities, fish species sold, biomass (kg) of each fish species sold, and income (€) resulting from each one of those fish species. Based on this information, the accumulated total catch per year for each of the species landed by the SSF fleet of Palamós was calculated.

Since knowledge on the Costa Brava SSF´s has been historically impeded by the high variety of fishing strategies deployed and the number of target species, it is necessary to present first a characterization of landing composition. With this aim, when possible, landings are determined to species level. Since species determination is undertaken by the operator of the fishermen guild, reports may not discriminate between closely related species, or misclassification a minor fraction of a species. In these cases, the species were regrouped at the family level. To validate or interpret species identification of landings a clear picture of local species composition and other information useful was obtained from the records of weekly onboard survey. For each of the identified species, conservation status was indicated as mentioned above (see 2.2.1).

2.2.4 Sampling for the morphometric data and histological assessment of gonads

Monthly samples were taken over a period of one year from December 2010 to November 2011. The sampling strategy was designed to achieve adequate sampling distribution through the seasons and sizes. Individuals of common pandora were obtained by the cooperation of local fishermen and for five types of fishing gears: traps, nets (gill nets and trammel nets), beach seine (sonsera), octopus traps and long-lines.

Individuals were sampled and processed the same day they were caught. The following information was collected from each fish: total length (TL, ±0.1 cm), total weight and eviscerated weight (TW and EW ±0.1 g), and gonad weight (GW ±0.1 g); sex and reproductive phase was recorded macroscopically. Gonads were removed from all specimens and fixed immediately in 4% buffered formaldehyde for histological processing.

2.3. Data analysis

2.3.1 Landed catch composition

Overall contribution of each species/groups in terms of biomass (kg) to the fishery was expressed as % of Accumulated Total Landed Catch (ATLC) of a given species for the period 2002–2011:

$$\mathrm{ATLC}i = \frac{\mathrm{ASLC}i\ \times\ 100}{\mathrm{TLC}}$$

where ASLC*i* is the accumulated total landed catch for the species *i* in the period and TLC is the total landed catch, considering the sum of all species/groups.

2.3.2 By-catch composition

To find cohesive groups of fishing events and by-catch species, a modularity analysis was applied. Modularity provides an objective approach to identify the number and size of those groups (Newman, 2006; Carstensen and Olesen, 2009). Herein, the modularity analysis was run on a presence–absence matrix of 152 fishing events × 125 by-catch species, that defines a bipartite or two-mode network—i.e., a network with two classes of nodes (fishing events and species), where links occur only among nodes of different classes, and are defined by the occurrence of a species in a fishing event. Thus, fishing events never connect with fishing events, and species never connect with species. In this context, modules correspond to species that are captured in similar fishing events and to fishing events that share species. Briefly, the method assumes that the data matrix (i.e., the bipartite network) can be divided naturally into groups (modules) and is the researcher task to find these modules (Newman, 2006). After the analysis, positive and large values of modularity indicate the occurrence of cohesive groups (Newman and Girvan, 2004). Following an optimization algorithm (simulated annealing), the analysis looks for the division that maximizes the modularity value (Newman and Girvan, 2004; Guimerà and Amaral, 2005). For a given partition, modularity value is given by the difference between the observed fraction of links connecting nodes (fishing events and species) in the same module and the expected fraction of links connecting nodes in the same module if connections were set by chance (Marquitti *et al*., 2013). The modularity analysis was performed with the software MODULAR (Marquitti *et al*., 2013), using the Barbermetric (2007) for bipartite networks. To evaluate its significance, the observed modularity was compared with an expected modularity distribution estimated on 2000 random networks (Marquitti *et al*., 2013). This analysis should provide a clear division of fishing events and by-catch species into modules not evident from other techniques.

2.3.2.1 Post-hoc analysis

In order to aid in the interpretation of the modules, were first examined the existence of correlations among two matrices depicting similarity between all possible pairs of fishing events; one matrix constructed using the commercial fraction of the catch and the other using the by-catch. The hypothesis tested was if the commercial fraction composition could be a useful explanatory variable of by-catch composition. To this end, a Mantel Test was performed between the two similarity matrices constructed using the Jaccard index. Once the composition of the commercial fraction was ruled out as an explanatory variable (see results), a post-hoc correspondence analysis was performed on a cross-tabulation table of standardized frequencies of potential explanatory variables (Greenacre, 1983). Then, for each module identified, were calculated the proportion of species within the categories of Orensanz and Jamieson (1998) and the proportion of fishing events performed with each sampling gear, adding to 9 explanatory variables. Finally, modules and explanatory variables were displayed in a two dimensional space, allowing formulating hypothesis on module composition based in the observed correlations.

Orensanz and Jamieson (1998) classification involve the following resource categories:: *Type 1*- sessile organisms of modular architecture which regenerate somatic material lost to a harvest (e.g. corals); *Type 2*- sedentary benthic organisms, including forms ranging from reduced motility (e.g. sea urchins, sea cucumbers, gastropods, most bivalves, etc.) to sessile (e.g. ascidians, most clams, etc.); *Type 3*- motile benthic or demersales organisms, typically residing for protracted periods in specific or structurally complex habitats (e.g., rocky or coral reefs). Examples include crabs and some shrimps, lobsters, octopus, and many fish species; *Type 4*- Highly motile demersales or pelagic species (e.g. majority of finfish stocks, jellyfish, shellfish, squid, etc.).

2.3.3 Temporal trends in the small-scale fisheries of Palamós

In order to assess changes in this specific SSF, the LPI was used, as proposed by Loh *et al*. (2005), and adapted by Collen *et al*. (2009). This index was originally based on a proportional change in abundance measure across all species from year to year. The basic idea is that species population trends can be used as a proxy of the state of the ecosystem that the species inhabit and can be constructed as indicators of biodiversity at any given scale (local, national, regional, or global levels), or by biome or biogeographic realm, if sufficient data exist. This information can be used to define and quantify the impact that humans are causing to the planet and for guiding actions to address biodiversity loss.

The annual LPI for fish population (hereafter LPI_{FP}) was calculated based on reported landed biomass based on daily data for 36 per species/groups (see Table 1) from 2002 to 2011, representing 90% of landings. These species/groups were represented evenly along the whole time-series, and are considered a fair representation of actual landings, since the auction is mandatory for the fishermen. Thus underreporting is considered negligible. To this end, the logarithm of the ratio of change for successive years (*d*) was calculate as

$$d_t = \log_{10} (N_t / N_{t-1})$$

where N is the landed biomass per species/groups and *t* is the year. Then, using species-specific values for d_t, the mean value was calculated across all species for each year

$$\bar{d}_t = \frac{1}{n_t} \sum_{i=1}^{n_t} d_{it}$$

where n (= 36) is the number of species/groups in year *t*. The index value (I) for each year (*t*) is calculated as

$$I_t = I_{t-1}\, 10^{d_t}$$

with the index value set to 1 in 2003.

It is recognized that landed biomass of a given species may not be an accurate proxy of the state of fish populations, since this does not take into account, for example, the size frequency distribution of individuals, and because this indicator may be affected by socio-economic drivers like market demand. However, in absence of good-quality estimators of population size, the LPI_{FP} can be interpreted as a raw indicator of population trends, as is the traditional usage of this index (Loh *et al.*, 2005), given associated information of the socio-economic setting.

The LPI for Fishing Effort (LPI_{FE}) and Direct Economic Benefits (LPI_{DEB}) also were calculated using the same procedure above detailed (in both cases, n = 1). For Fishing Effort, N was expressed as the total number of fishing trips per year. Each fishing trip often implies the usage of several gears. Unfortunately, the information gathered by the fishermen guild does not allow us to associate a given fishing operation with a particular fishing gear. Conversely, N for Direct Economic Benefits was expressed as total revenues (as percentage of national GDP) per year in Palamós port, according to auction notes. Daily sales were reported in Euros, and standardized using the GDP at purchaser's prices (constant 2005 US$), retrieved form World Bank Statistics (http://data.worldbank.org). Thus, this suite of indicators provide insights into the state of biodiversity as expressed in the LPI_{FP}, but also of socio-economic features of the fishery, since LPI_{FE} can be seen as a raw proxy of costs, while the LPI_{DEB} can be directly related to the economic impacts of the fishery. This indicator is a fishery-specific version of "Total landed value of marine fisheries as % of GDP", selected as a macro indicator for both trend and state under "Human Dimensions Indicators" by INDISEAS (available at www.indiseas.org). However, total revenues or retail sales generated are only one component of the economic benefits, for it should also consider the resulting direct and indirect jobs (either on-board or land-based), tax revenues, and other economic effects. By-catch was not considered in this work since there are no data available in the records from the fishermen guild, but information on this component can be found in Dimitriadis *et al*., (2015a).

The ordinary least-square regressions were used over the temporal series of the indices calculated for depicting temporal trends and correlations among them. Sample autocorrelation analysis (Durbin-Watson) of the regression residuals was performed to detect the effects of serial correlation. An outlier analysis was also performed, removing the effects of an unusual observation, more likely related to meteorological and/or operational issues. This decision was taken after recovering the opinion of local fishermen.

2.3.4 Histological assessment of gonad development and sexual cycle of Pagellus erythrinus

2.3.4.1 Reproductive status

Histological analysis of the gonads was performed in three sections of the gonad: anterior, central and posterior, founding the central portion to be the one that better described the changes in its condition. Therefore, central portions of the fixed gonads were extracted, dehydrated, and embedded in paraffin. The paraffin embedding protocol is described in Table 2.

Table 2: Protocol paraffin embedding used along this study.

Step	Chemical	Time (h)
1	Ethanol 96%	1:30
2	Ethanol 96%	1:00
3	Ethanol 100%	1:00
4	Ethanol 100%	1:00
5	Ethanol 100%	1:00
6	Eucalyptol essence	12:00 – 24:00
7	Xylene	1:00
8	Xylene	1:00
9	Paraffin*	5:30
10	Paraffin*	3:00

The blocks obtained were sectioned at 5-10 µm on a rotary microtome Medin, depending on the gonad maturation stage, and stained with hematoxylin-eosin. This staining method is the most common staining technique used for histological analyses on reproductive biology of fishes (Saborido-Rey and Junquera, 1998) due to its simplicity and standardization. With this staining procedure eosinophilic structures acquire a red colour in bright field microscopy, while the rest of the substrates obtain a blue coloration due to haematoxylin staining. A detail of staining procedure is described in Table 3.

Table 3: Hematoxylin-Eosin staining protocol used along this study. Steps 1 to 6 correspond to the dewaxing process. The remaining steps are for the staining.

Step	Chemical	Time (min)
1	Xylene	15:00
2	Xylene	15:00
3	Ethanol 100%	5:00
4	Ethanol 96%	5:00
5	Ethanol 70%	5:00
6	Distilled water	1:00
7	Delafield Hematoxylin	2:00
8	Distilled water	0:02
9	Ethanol Amoniacal	5:00
10	Distilled water	0:02
11	Aqueous Eosin (1%)	10:00
12	Ethanol 70%	2:00
13	Ethanol 96%	2:00
14	Ethanol 100%	2:00
15	Eucalyptol essence	15:00
16	Xylene	3:00
17	Xylene	3:00

To confirm sexual patterns, a histological examination of specific gonadal features was conducted and the ovarian development phases were determined following the procedure from Brown-Peterson *et al*. (2011).

Reproductive phases (Table 3) are defined as immature (I), regenerating (RN), developing (D), spawning capable (SC), actively spawning (AS) and regressing (RG). For testicular tissue, germ cells were classified based on histological criteria into the stages of development described by Grier (1981) and the determination of male reproductive phases was based on the criteria presented by Brown-Peterson *et al*. (2011) (Table 4).

Table 4: Description gonad developmental characteristics of the different stages of the reproductive cycle for female and male fishes. Based on histological maturity classification criteria from Brown-Peterson *et al*. (2011). CA: cortical alveolar, GVBD: germinal vesicle breakdown, GVM: germinal vesicle migration, OM: oocyte maturation, PG: primary growth, POF: postovulatory follicle complex, Vtg1: primary vitellogenic, Vtg2: secondary vitellogenic, Vtg3: tertiary vitellogenic, GE: germinal epithelium, Sc1: primary spermatocyte, Sc2: secondary spermatocyte, Sg1: primary spermatogonial, Sg2: secondary spermatogonial, St: spermatid, Sz: spermatozoa.

Phase			Female	Male
Immature		Never spawned	Only oogonia and PG oocytes present. No atresia or muscle bundles. Thin ovarian wall and little space between oocytes.	Only primary spermatogonia present. No lumen in lobules.
Mature	Developing	Gonads beginning, to develop, will not spawn soon	PG, CA, Vtg1, and Vtg2 oocytes present. No evidence of POFs or Vtg3 oocytes. Some atresia can be present.	Spermatocysts evident along lobules. Sg2, Sc1, Sc2, St, and Sz can be present in spermatocysts. Sz not present in lumen of lobules or in sperm ducts. GE continuous throughout.
	Spawning Capable	Fish will spawn in this season	Vtg3 oocytes present or POFs present in batch spawners. Atresia of vitellogenic and/or hydrated oocytes may be present. Early stages of OM can be present.	Sz in lumen of lobules and/or sperm ducts. All stages of spermatogenesis can be present. Spermatocysts throughout testis, active spermatogenesis. GE can be continuous or discontinuous.
	Actively Spawning	Imminent, active or recent spawning	oocytes undergoing late GVM, GVBD, hydration, or ovulation.	Sz in lumen of lobules and/or sperm ducts. All stages of spermatogenesis can be present. Spermatocysts throughout testis, active spermatogenesis. GE can be continuous or discontinuous.

Regressing	Cessation of spawning	Atresia (any stage) and POFs present. Some CA and/or vitellogenic (Vtg1, Vtg2) oocytes present.	Residual Sz present in lumen of lobules and in sperm ducts. Widely scattered spermatocysts near periphery containing Sc2, St, Sz. Little to no active spermatogenesis. Spermatogonial proliferation and regeneration of GE common in periphery of testes.
Regenerating	Sexually mature, reproductively inactive	Only oogonia and PG oocytes present. Muscle bundles, enlarged blood vessels, thick ovarian wall and/or gamma/delta atresia or old, degenerating POFs may be present.	No spermatocysts. Lumen of lobule often nonexistent. Proliferation of spermatogonia throughout testes. GE continuous throughout. Small amount of residual Sz occasionally present in lumen of lobules and in sperm duct.

2.3.4.2 Cross-validation of morphological and histological sex determination

In order to evaluate possible misclassification of gonads, two people independently identified visually the sex of each gonad. Such identification was compared later with the results obtained by histological analysis.

2.3.4.3 Population parameters

In order to highlight changes in fish maturity and identify the spawning period, a monthly gonadosomatic index (GSI) was calculated and plotted over the year. For each individual, this index was calculated as:

$$GSI = \frac{GW}{EW} \times 100$$

and gonads from juvenile female specimens were not considered.

Significant differences in monthly GSI values among sexes were assessed with the Kruskal-Wallis test because homogeneity of variance and homoscedasticity assumptions were not met. Furthermore, relative frequencies of different maturity stages along the year were plotted, in order to determine if specific stages were predominantly occurring.

The sex-ratio (number of females: number of males) was estimated and performed a χ^2 test to reveal any significant differences from the expected ratio (1:1). Length-frequency diagrams were also obtained from fish lengths classified in 2.0 cm group intervals. Since homogeneity of variance and homoscedasticity assumptions were not met, were analyzed the total length data using the non-parametric Kruskal-Wallis test of significance.

Estimates of the proportion of mature individuals as a function of size were used to model a logistic maturity function and to estimate the average size at maturity, as follows (King, 2007)

$$P(Li) = {}^{1}\!/_{1\,+\,e^{(a+b*TL)}},$$

where P(L*i*) is the proportion of mature individuals in the class *i*, and *a* and *b* are parameters. The average size at sexual maturity (L_{50}) was obtained by L_{50}=-a / b, where *a* and *b* are parameters defined in the previous equation. Estimation of TL at sex change was conducted using generalized linear models (GLM) with a quasibinomial family function (Zuur *et al*., 2007).

2.3.4.4 Fisheries Data

The impact caused by the small-scale fishery on the common pandora, was assessed by calculating the mean catch size (MCS) for each gear (Narvaéz *et al*., 2008), and the monthly variations of the MCS was assessed using the Kruskal-Wallis test. As output of the analysis were plotted the estimated MCS (±SE) for each fishing gear versus its corresponding size at sexual maturity (L_{50}), understood as catch size limit below which the spawning stock could be threatened (Rueda and Defeo, 2003) and with the LT at sex change. Additionally, were assessed different possible fishery status scenarios using L_{50} value, the TL at sex change and its upper CI 95% level as limit reference points (LRPs).

CHAPTER 3

RESULTS

3.1 Landed catch composition and conservation status

At least 128 species/groups belonging to 59 families and 78 genera were landed during the study period (Table 5). Some species were grouped due to their very low overall representation or to reflect the grouping made by fishers, resulting in 92 categories. Ammodytidae (26.8%) was the most frequent fish family occurring in catches followed by Scombridae (12.4%), Merluciidae (10.1%), and Sparidae (9.3%). The families with the largest number of species were Sparidae (12), Labridae (5), and Rajidae (5). Five species contributed to over 50% of the landings, being *Gymnammodytes spp*. (26.8%) followed by *Merluccius merluccius* (10.1%) being the single most important species (Figure 4). Some 5.1% of landings were coded as miscellaneous, including few individuals from several species that are sold together in the same box. This is a very common form of sale that is made to streamline the sales process in the auction and to generate interest from buyers.

The 48.9% of groups found were listed in the global red list of the International Union for Conservation of Nature (IUCN, 2014; Table 5). 3.3 % of the species landed were categorized as Endangered (EN) by IUCN, 3.3% as Vulnerable (VU), 4.3% as Near Threatened (NT), and 35.9% as Least Concern (LC). The remaining 2.2% were considered Data Deficient (DD); while the rest of species caught (53.3 %) were not currently evaluated.

The 10.9% of groups found were included at least in one of the following multilateral agreements: Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR, 2008), the United Nations Convention on the Law of the Sea (UNCLOS, 1982), Convention on the Conservation of European Wildlife and Natural

Table 5: Species caught by the small-scale fishing fleet of the port of Palamós (NW Mediterranean) during the study period. Some species were grouped due to their very low overall representation or to reflect fishermen categorization. Overall percentage of total landing weight is shown. * Species identified in the sampling and not recorded at the auction of fishermen guild. + Species used to estimate trends in the LPI. No id.: not identified to species level. IUCN: International Union for Conservation of Nature, species included in the Red List of threatened species. IUCN – MED: Red List of threatened Species – Regional Assessment for the Mediterranean Sea. OSPAR: Commission, protecting and conserving the North-East Atlantic and its resources. Species located in OSPAR Regions. UNCLOS: United Nations Convention on the Law of the Sea. Species listed in Annex I, as highly migratory. BERN: Bern Convention. Species included in appendices. BARCOM: Barcelona Convention for Protection against Pollution in the Mediterranean Sea. Species contained in annexes. STECF: Scientific, Technical and Economic Committee for Fisheries - European Union. Species included in the geographical sub area 6.

Family	Species	IUCN	IUCN-Med	Other
Gadidae	*Trisopterus minutus* +	LC	LC	
Gobiidae	*Pseudaphya ferreri*	LC	LC	
Phycidae	*Phycis spp.*[1]	NE	LC	
Sparidae	*Dentex dentex*	VU (A2bd)	VU	
	Oblada melanura +	LC	LC	
	Pagellus acarne+	LC	LC	
	Pagellus bogaraveo	NT	LC	
	Pagellus erythrinus +	LC	LC	
	Pagrus pagrus	LC	LC	
	Sarpa salpa	LC	LC	

[1] *Phycis blennoides / Phycis phycis*

	Sparus aurata +	LC	LC	
	Spondyliosoma cantharus	LC	LC	
Trichiuridae	*Lepidopus caudatus*	NE	LC	
Zeidae	*Zeus faber* +	NE	LC	
Ammodytidae	*Gymnammodytes spp.*[2]	NE	LC	
Bothidae	*Bothus podas* *	NE	LC	
Cepolidae	*Cepola macrophthalma*	NE	LC	
Citharidae	*Citharus linguatula* +	NE	LC	
Congridae	*Conger conger* +	NE	LC	
	Coris julis	LC	LC	
Labridae	*Labrus merula* *	LC	LC	
	Labrus viridis *	VU (A4ad)	VU	
	Shymphodus (Crenilabrus) tinca *	NE	LC	
	Xyrichtys novacula	LC	LC	
Lophiidae	*Lophius spp.*[3]	NE	LC	
Lotidae	*Molva dypterygia*	NE	LC	
Merluciidae	*Merluccius merluccius* +	NE	VU	Overexploited - STECF
Moronidae	*Dicentrarchus labrax* +	LC	NT	
Mullidae	*Mullus spp.*[4]	NE	LC	Overexploited - STCEF
Polyprionidae	*Polyprion americanus*	DD	DD	

[2] *Gymnammodytes cicerelus / Gymnammodytes semisquamatus*
[3] *Lophius piscatorius / Lophius budegassa*
[4] *Mullus barbatus / Mullus surmuletus*

Pomacentridae	*Chromis chromis* *	NE	LC	
Rajidae	*Raja asterias*	LC	LC	
	Raja brachyura *	NT	DD	
	Raja montagui *	LC	LC	OSPAR: II, III, IV, V
	Raja polystigma *	NT	NT	
	Raja undulata *	EN (A2bd+3d+4bd)	EN	
Sciaenidae	*Sciaena umbra*	NE	VU	OSPAR: II, III, IV, V
Scoptthalmidae	*Lepidorhombus spp.*[5]	NE	LC	
	Scopthhalmus spp.[6]	NE	LC	
Scorpaenidae	*Scorpaena spp.*[7]	NE	LC	
Scyliorhinidae	*Scyliorhinus canicula*	LC	LC	
Sebastidae	*Helicolenus dactylopterus* +	NE	LC	
Serranidae	*Epinephelus marginatus*	EN (A2d)	EN	BERN: III/ BARCOM: III
	Serranus spp.[8]	NE	LC	
Soleidae	*Solea solea* +	NE	LC	
Sparidae	*Boops boops* +	LC	LC	
	Diplodus spp.[9]	LC	LC	
	Lithognathus mormyrus	LC	LC	

[5] *Lepidorhombus whiffiagonis / Lepidorhombus sp.*
[6] *Scophthalmus maximus / Scophthalmus rhombus*
[7] *Scorpaena porcus / Scorpaena notata / Scorpaena scrofa*
[8] *Serranus cabrilla / Serranus scriba*
[9] *Diplodus sargus / Diplodus cervinus / Dipodus vulgaris / Diplodus puntazzo*

Trachinidae	*Trachinus draco*+	NE	LC	
	Trachinus radiates	NE	LC	
Triglidae	*Eutrigla gurnardus* *	NE	LC	
Triglidae	*No id.*[10]	NE	LC	
Uranoscopidae	*Uranoscopus scaber* +	NE	LC	
Argentinidae	*Argentina sphyraena*	NE	LC	
Belonidae	*Belone belone*	NE	NE	
Carangidae	*Thrachurus spp.*[11]	NE	LC	
Centracanthidae	*Spicara spp.*[12]	LC	LC	
Clupeidae	*Sardina pilchardus*	NE	LC	
Coryphaenidae	*Coryphaena hippurus*	LC	LC	
Engraulidae	*Engraulis encrasicolus*	NE	LC	
Sphyraenidae	*Sphyraena spp.*[13]	NE	LC	
Gadidae	*Micromesistius poutassou* +	NE	LC	Overexploited - STECF
Scombridae	*Auxis rochei rochei*	LC	LC	UNCLOS: SI
Bramidae	*Brama brama* +	NE	DD	
Carangidae	*Seriola dumerili*	NE	LC	
Clupeidae	*Sardinella aurita*	NE	LC	

[10] *Chelidonichthys lucerna / Chelidonichthys obscurus / Trigloporus lastoviza / Chelidonichthys lucerna / Lepidotrigla cavillone / Trigla lyra*
[11] *Trachurus trachurus / Trachurus mediterraneus*
[12] *Spicara maena / Spicar smaris*
[13] *Sphyraena viridensis / Sphyraena sphyraena*

Mugilidae	*No id.*[14]	LC	LC	
Pomatomidae	*Pomatomus saltatrix*	NE	LC	
Scombridae	*Sarda sarda* [+]	LC	LC	
	Thunnus thynnus	EN (A2bd)	EN	OSPAR: V/ UNCLOS: SI/ BARCOM: III
	No id.[15]	NT	NE	
Xiphiidae	*Xiphias gladius* [+]	LC	NT	UNCLOS: SI/ BARCOM: III
Veneridae	*Ruditapes decussatus*	NE	NE	
Loliginidae	*Alloteuthis spp.*[16]	NE	NE	
	Loligo spp.[17]	NE	NE	
Octopodidae	*No id.* [+18]	NE	NE	
Ommastrephidae	*No id.* [+19]	LC	NE	
Sepiidae	*No id.* [+20]	LC	NE	
Cassidae	*Galeodea rugosa*	NE	NE	
Muricidae	*Bolinus brandaris*	NE	NE	
	Stramonita haemastoma	NE	NE	
Calappidae	*Calappa granulata*	NE	NE	

[14] *Liza aurata / Liza ramada / Mugil cephalus*
[15] *Thunnus alalunga / Euthynnus alletteratus / Scomber japonicus / Scomber scombrus*
[16] *Alloteuthis subulata / Alloteuthis media*
[17] *Loligo reynaudi / Loligo vulgaris*
[18] *Octopus vulgaris / Eledone cirrhosa*
[19] *Todarodes sagittatus / Illex coindetii*
[20] *Sepia officinalis / Sepia elegans / Sepia orbignyana*

Homolidae	*Paromola cuvieri*	NE	NE	
Munididae	*Munida spp.*[21]	NE	NE	
Nephropidae	*Homarus gammarus*	LC	NE	BERN: III/ BARCOM: III
	Nephrops norvegicus	LC	NE	Overexploited - STECF
Palinuridae	*Palinurus elephas* +	VU (A2bd)	NE	BERN: III/ BARCOM: III
Palinuridae	*Palinurus mauritanicus*	LC	NE	
Polybiidae	*Liocarcinus depurator*	NE	NE	
Scyllaridae	*Scyllarus arctus*	LC	NE	
				BERN: III/ BARCOM: III
Echinidae	*Paracentrotus lividus* +	NE	NE	BERN: III/ BARCOM: III
Holothuriidae	*No id.*[22]	LC	NE	

[21] *Munida rugosa / Munida intermedia*
[22] *Parastichopus regalis / Holothuria tubulosa / Holothuria forskali*

Habitats (BERN, 1979), and the Barcelona Convention for Protection against Pollution in the Mediterranean Sea (BARCOM, 1995). Few species were shared by more than one of the above mentioned agreements (ca. 9.0%), while 87% of the species were not included in any agreements. None of the species were included under the Habitats Directive of the EU (Habitats Directive, 1992).

However, for stocks with regional (i.e. Mediterranean) IUCN assessment, (see Abdul Malak *et al*., 2011), 10.9% of groups were listed under some threat category (Table 5). Of these, 3.3% were listed as EN, 4.3% as VU, 3.3 as NT and the 4.2% were considered DD. Four of those species were also listed in the BERN, BARCOM, OSPAR and UNCLOS (Table 4), and one (*Merluccius merluccius*) was considered overexploited by the Scientific, Technical and Economic Committee for Fisheries (STECF). The remaining 63% of the species were listed as LC, while 25% of species were not currently evaluated. Of the species not assessed by the IUCN in the Mediterranean, four were included in annexes to BERN and BARCOM and one (*Nephrops norvegicus*) was considered overexploited by STECF. Furthermore, two species listed as LC were included at list in OSPAR and UNCLOS, while two species (*Micromesistius poutassou* and *Mullus barbatus*) were assessed as overexploited by the STECF.

3.2 By-catch Composition and Conservation status

A total of 147 species belonging to 96 families and 130 genera occurred as by-catch during the study period (Tables 6 and 7). Considering fish species, the families with the largest number of species were Sparidae (12) followed by Rajidae (3), Scombridae (3), Scorpaenidae (3) and Carangidae (3). For invertebrates, Alcyoniidae, Diogenidae and Epialtidae were the families with most species (3).

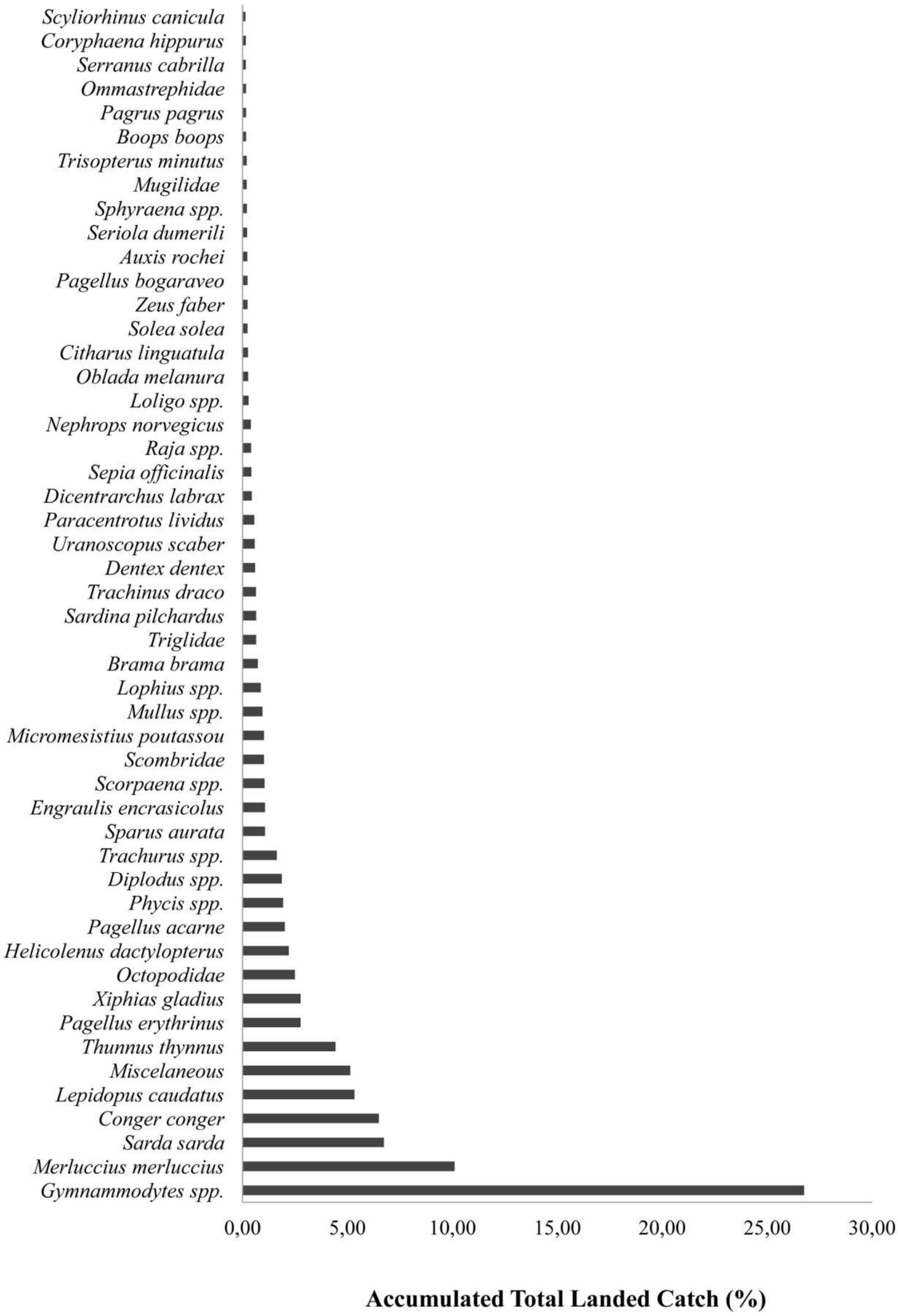


Figure 4: Accumulated Total Landed Catch of species caught by the small-scale fleet of the port of Palamós (NW Mediterranean) during 2002 - 2011. Species with a total accumulated catch ≥ 0.1.

Some 87.3% of fish species presented commercial interest, while this hold true for 15.5% of invertebrates. These species are mainly discarded to be rotten, bitten, small size, used as bait or for own consumption. The information concerning target species is presented in Dimitriadis *et al*. (2015b).

Thet 23.8% of species were listed in the global red list of the International Union for Conservation of Nature (IUCN, 2014; Tables 6 and 7). 0.7% of the by-catch species were categorized as Endangered (EN) by IUCN, 2.0% as Vulnerable (VU), 1.4% as Near Threatened (NT), and 17% as Least Concern (LC). The remaining 2.7% were considered Data Deficient (DD); while the rest of by-catch species (76.9%) were not currently evaluated. It is important to stress that the 49.2% of the fish species were classified into one of the categories of the IUCN, while only 4.8% of invertebrates were catalogued.

The 4.8% of by-catch species were included at least in one of the following multilateral agreements: OSPAR (OSPAR, 2008), UNCLOS (UNCLOS, 1982), BERN (Bern Convention, 1979), and BARCOM (Barcelona Convention, 1995). Few species were shared by more than one of the above mentioned agreements (ca. 4.1%), while 95.2% of the species were not included in any agreements. Only one species were included under the Habitats Directive of the EU (Habitats Directive, 1992).

However, for species with regional (i.e., Mediterranean) IUCN assessment, 40.1% of species were listed under some threat category (Tables 1 and 2). Of these, 2.0% were listed as VU, 36.7% as LC and the 1.4% was considered DD. Of these species, *Merluccius merluccis* and *Mullus barbatus* are considered overexploited by the STECF

(STECF, 2014). Furthermore, one species listed as LC were list in UNCLOS and another was included in annexes to BERN and BARCOM conventions (Tables 6 and 7). Of the species not assessed by the IUCN in the Mediterranean (58.5%), four were included in annexes to BERN and BARCOM and one (*Corallium rubrum*) was included under the Habitats Directive of the EU.

3.2.1 Modularity analysis and module interpretation (post-hoc analysis)

The network of fishing events and by-catch species (nodes and 818 links) presented a significantly modular structure (M= 0.43; $p < 0.05$), composed by nine modules or discrete putative management units. The number of nodes in modules ranged from 2 (1 fishing event and 1 species) to 56 (35 fishing events to 21 species) (Figure 5). The modularity analysis requires a connected network to run, so some species and fishing events were not considered since were disconnected from the major component of the network (see Tables 6 and 7).

According to the Mantel test, similarity in by-catch composition among fishing events is uncorrelated with similarity in composition of the commercial fraction ($r = 0.008$, $p < 0.001$), and thus module membership cannot be explained on this basis.

Table 6: By-catch fish species by the small-scale fishing fleet of the port of Palamós (NW Mediterranean) during the study period. IUCN: International Union for Conservation of Nature, species included in the Red List of threatened species. IUCN –MED: Red List of threatened Species – Regional Assessment for the Mediterranean Sea. UNCLOS: United Nations Convention on the Law of the Sea. Species listed in Annex I, as highly migratory. BERN: Bern Convention. Species included in appendices. BARCOM: Barcelona Convention for Protection against Pollution in the Mediterranean Sea. Species contained in annexes. HD: Habitats Directive. Species included in annexes. DBC: discarded by-catch. RBC: retained by-catch. * Species not included in the modularity analysis. + Commercial target species.

Family	Species	Module	Fate	IUCN	IUCN-Med	Other
Gadidae	*Trisopterus spp.*[23]	3	DBC – rotten	LC	LC	
Phycidae	*Phycis blennoides**+	-	DBC - rotten	NE	LC	
Phycidae	*Phycis physis* +	4	DBC - rotten	NE	LC	
Sparidae	*Dentex dentex* +	5	RBC – own consumption	VU (A2bd)	VU (A2bd)	
Sparidae	*Oblada melanura*	0	RBC – own consumption	LC	LC	
Sparidae	*Pagellus spp.*[24] +	6	RBC – own consumption/bait	LC	LC	
Sparidae	*Pagrus pagrus* +	7	DBC - rotten	LC	LC	
Sparidae	*Sarpa salpa*	6	DBC - rotten	LC	LC	
Sparidae	*Sparus aurata* +	0	RBC – own consumption	LC	LC	
Sparidae	*Spondyliosoma cantharus*+	6	DBC - bitten	LC	LC	
Zeidae	*Zeus faber* +	3	DBC - rotten	NE	LC	

[23] *T. minutus* / *T. luscus*
[24] *P. acarne* / *P. bogaraveo* / *P. erythrinus*

Bothidae	*Bothus podas* +	6	DBC - rotten	NE	LC	
Citharidae	*Citharus linguatula* +	2	DBC - rotten	NE	LC	
Congridae	*Conger conger*	0	RBC - own consumption/bait	NE	LC	
Dasyatidae	*Dasyatis pastinaca**	-	DBC	DD	NE	
Gobiidae	*Gobius niger jozo*	0	DBC	NE	LC	
Labridae	*Coris julis*	0	RBC - bait	LC	LC	
Labridae	*Symphodus spp.*[25]	0	RBC - bait	LC	NE	
Lophiidae	*Lophius spp.*[26]	3	DBC - rotten	NE	LC	
Merluciidae	*Merluccius merluccius* +	3	DBC - rotten	NE	VU (A2bd)	Overexploited – STECF
Mullidae	*Mullus spp.*[27] +	6	DBC - rotten	NE	LC	Overexploited – STECF
Muraenidae	*Muraena helena*	4	DBC	NE	LC	
Myliobatidae	*Myliobatis aquila*	2	DBC	DD	DD	
Pomacentridae	*Chromis chromis*	0	RBC - bait	NE	LC	
Rajidae	*Raja asterias*	6	DBC – small size	LC	LC	
Rajidae	*Raja brachyura*	6	DBC	NT	NE	
Rajidae	*Raja undulata*	8	DBC	ENA2bd+3d+4bd	NE	
Sciaenidae	*Sciaena umbra* +	3	DBC - rotten	NE	VU (A2acd)	BERN: III/ BARCOM: III
Scorpaenidae	*Scorpaena spp.*[28] +	0	RBC - own consumption/bait	NE	LC	

[25] *S. tinca* / *S. (Crenilabrus) mediterraneus*
[26] *L. budegassa* / *L. piscatorius*
[27] *M. barbatus* / *M. surmuletus*
[28] *S. notata* / *S. porcus* / *S. scrofa*

Scyliorhinidae	*Scyliorhinus canicula*	3	DBC	LC	LC	
Serranidae	*Serranus cabrilla*	7	RBC - own consumption/bait	NE	LC	
Sparidae	*Boops boops*	8	DBC - few individuals/bitten	LC	LC	
Sparidae	*Diplodus sargus* +	0	RBC - bait	LC	LC	
Sparidae	*Diplodus vulgaris* +	0	RBC - bait	LC	LC	
Synodontidae	*Synodus saurus*	8	DBC	LC	LC	
Torpedinidae	*Torpedo marmorata*	6	DBC	DD	NE	
Torpedinidae	*Torpedo nobiliana*	6	DBC	DD	NE	
Trachinidae	*Trachinus spp.*[29]	6	RBC - own consumption	NE	LC	
Triglidae	No id.[30]*	-	-	NE	LC	
Uranoscopidae	*Uranoscopus scaber* +	6	DBC - rotten	NE	LC	
Belonidae	*Belone belone*	2	DBC - low commercial value	NE	LC	
Carangidae	*Trachurus spp.*[31]	6	retained by-catch	NE	LC	
Centracanthidae	*Spicara maena**	-	RBC - bait	LC	LC	
Centracanthidae	*Spicara smaris*	4	RBC - bait	LC	LC	
Clupeidae	*Sardinella aurita*	8	RBC - own consumption	NE	LC	
Sphyraenidae	*Sphyraena spp.*[32]*	-	DBC - low commercial value	NE	LC	
Scombridae	*Auxis rochei* +	2	DBC - rotten	LC	LC	UNCLOS

[29] *T. draco* / *T. radiatus*
[30] *Chelidonichthys lucerna* / *Chelidonichthys obscurus* / *Trigloporus lastoviza* / *Lepidotrigla cavillone* / *Trigla lyra*
[31] *T. mediterraneus* / *T. trachurus*
[32] *S. viridensis* / *S. sphyraena*

Carangidae	*Seriola dumerili* [+]	8	DBC - rotten	NE	LC
Molidae	*Mola mola*	3	DBC	NE	DD
Mugilidae	*Liza aurata*	5	DBC - low commercial value	LC	LC
Mugilidae	*Liza ramada*	2	RBC - bait	LC	LC
Scombridae	*Sarda sarda* [+]	5	RBC - own consumption	LC	LC
Scombridae	*Scomber japonicus*	5	DBC - rotten	LC	LC

Table 7: By-catch invertebrate species by the small-scale fishing fleet of the port of Palamós (NW Mediterranean) during the study period. IUCN: International Union for Conservation of Nature, species included in the Red List of threatened species. IUCN – MED: Red List of threatened Species – Regional Assessment for the Mediterranean Sea. BERN: Bern Convention. Species included in appendices. BARCOM: Barcelona Convention for Protection against Pollution in the Mediterranean Sea. Species contained in annexes. HD: Habitats Directive. Species included in annexes. DBC: discarded by-catch. RBC: retained by-catch. * Species not included in the modularity analysis. + Commercial target species.

Family	Species	Module	Fate	IUCN	IUCN-Med	Other
Alcyoniidae	*Alcyonium acaule*	3	DBC	NE	NE	
Alcyoniidae	*Alcyonium coralloides*	3	DBC	NE	NE	
Alcyoniidae	*Alcyonium palmatum*	3	DBC	NE	NE	
Ascidiidae	No id.*	-	DBC			
Ascidiidae	*Phallusia mammillata*	2	DBC	NE	NE	
Axinellidae	*Axinella spp.*[33]	3	DBC	NE	NE	BERN: II / BARCOM: II
Bitectiporidae	*Pentapora fascialis*	3	DBC	NE	NE	
Caryophylliidae	*Caryophyllia spp.*	3	DBC	NE	NE	
Corallidae	*Corallium rubrum*	2	DBC	NE	NE	HD: V / BARCOM: III / BERN: III
Demospongiae	No id.*	-	DBC			
Didemnidae	*Polysincraton lacazei*	3	DBC	NE	NE	
Dysideidae	*Pleraplysilla spinifera*	3	DBC	NE	NE	
Funiculinidae	*Funicula quadrangularis*	3	DBC	NE	NE	

[33] *A. polypoides* / *A. verrucosa* / *A. damicornis*

Gorgoniidae	*Eunicella spp.*[34]	3	DBC	VU (A1d)	NE
Gorgoniidae	*Leptogorgia sarmentosa*	3	DBC	NE	NE
Hormathiidae	*Calliactis parasitica*	7	DBC	NE	NE
Hymedesmiidae	*Hymedesmia spp.*	3	DBC	NE	NE
Ianthellidae	*cf Hexadella racovitzai**	-	DBC	NE	NE
Irciniidae	No id.	3	DBC		
Myriaporidae	*Myriapora truncata*	4	DBC	NE	NE
Parazoanthidae	*Parazoanthus axinellae*	3	DBC	NE	NE
Pennatulidae	*Pennatula rubra*	8	DBC	NE	NE
Phidoloporidae	*Reteporella spp.*	3	DBC		
Plexauridae	*Paramuricea spp.*[35]	3	DBC	NE	NE
Pyuridae	*Halocynthia papillosa*	7	DBC	NE	NE
Pyuridae	*Microcosmus spp.*[36]	3	DBC	NE	LC
Smittinidae	*Smittina cervicornis*	3	DBC	NE	NE
Veretillidae	*Veretillum cynomorium*	7	DBC	NE	NE
Antedonidae	*Antedon mediterranea*	0	DBC	NE	NE
Aplysiidae	*Aplysia spp.*[37]	0	DBC	NE	NE
Aporrhaidae	*Aporrhais serresianus*	3	DBC	NE	NE

[34] *E. cavolinii* / *E. singularis* / *E. verrucosa*
[35] *P. clavata* / *P. macrospina*
[36] *M. sabatieri* / *M. squamiger* / *M. exasperatus* / *M. poutassou*
[37] *A. punctata* / *A. fasciata*

Asteriidae	*Coscinasterias tenuispina*	7	DBC	NE	NE	
Asteriidae	*Marthasterias glacialis*	7	DBC	NE	NE	
Astropectinidae	*Astropecten aranciacus*	7	DBC	NE	NE	
Chaetasteridae	*Chaetaster longipes*	3	DBC	NE	NE	
Echinasteridae	*Echinaster sepositus**	-	DBC	NE	NE	
Gorgonocephalidae	*Astrospartus mediterraneus*	3	DBC	NE	NE	
Holothuriidae	No id.[38]*	-	RBC - bait	LC	NE	
Muricidae	*Bolinus brandaris*	6	RBC - own consumption	NE	NE	
Muricidae	*Hexaplex trunculus*	4	RBC - own consumption	NE	NE	
Ophidiasteridae	*Hacelia attenuata*	2	DBC	NE	NE	
Ophiodermatiidae	*Ophioderma longicauda*	7	DBC	NE	NE	
Ophiotrichidae	*Ophiothrix spp.*[39]	7	DBC	NE	NE	
Parechinidae	*Paracentrotus lividus*	4	DBC	NE	NE	BERN: III/ BARCOM: III
Pectinidae	*Mimachlamys varia*	2	DBC	NE	NE	
Pectinidae	*Pecten jacobaeus*	6	DBC	NE	NE	
Toxopneustidae	*Sphaerechinus granularis*	7	DBC	NE	NE	
Turritellidae	*Turritella turbona*	7	DBC	NE	NE	
Acoetidae	*Polyodontes maxillosus*	1	DBC	NE	NE	

[38] *Parastichopus regalis* / *Holothuria tubulosa* / *Holothuria forskali*
[39] *Ophiothrix fragilis* / *Ophiothrix quinquemaculata*

Calappidae	*Calappa granulata*	6	RBC - own consumption	NE	NE	
Diogenidae	*Dardanus arrosor*	7	RBC - bait	NE	NE	
Diogenidae	*Dardanus calidus*	4	RBC - bait	NE	NE	
Diogenidae	*Paguristes eremita*	0	DBC	NE	NE	
Dromiidae	*Dromia personata*	2	RBC - bait	NE	NE	
Epialtidae	*Herbstia condyliata*	8	DBC	NE	NE	
Epialtidae	*Lissa chiragra*	8	DBC	NE	NE	
Epialtidae	*Pisa armata*	8	DBC	NE	NE	
Galatheidae	*Galathea strigosa*	4	RBC - own consumption/bait	NE	NE	
Homolidae	*Paromola cuvieri*+	3	DBC - alive	NE	NE	
Inachidae	*Macropodia spp.*[40]*	-	DBC	NE	NE	
Majidae	*Maja crispata*	2	DBC	NE	NE	
Octopodidae	*Octopus vulgaris*+	7	RBC - bait	NE	NE	
Palinuridae	*Palinurus elephas*+	3	DBC - rotten	VUA2bd	NE	BERN: III/ BARCOM: III
Parthenopidae	*Derilambrus angulifrons*	6	DBC	NE	NE	
Pilumnidae	*Pilumnus spinifer*	6	DBC	NE	NE	
Polybiidae	No id.[41]*	-	DBC	NE	NE	
Scylaridae	*Scyllarus arctus**	-	RBC - own consumption/bait	LC	LC	BERN: III/ BARCOM: III

[40] *M. longirostris* / *M. rostrata*
[41] *Macropipus tuberculatus* / *Necora puber* / *Liocarcinus depurator* / *Liocarcinus corrugatus*

Sepiidae	*Sepia officinalis*[+]	6	RBC - own consumption/bait	LC	LC
Squillidae	*Squilla mantis*	3	DBC	NE	NE
Cepheidae	*Cotylorhiza tuberculata*	4	DBC	NE	NE
Loliginidae	*Loligo spp.*[42+]	8	RBC - own consumption	NE	NE
Pelagiidae	*Pelagia noctiluca*	8	DBC	NE	NE
Rhizostomatidae	*Rhizostoma pulmo*	2	DBC	NE	NE
Salpidae	*Salpa spp.*[43]	3	DBC	NE	NE

[42] *L. vulgaris* / *L. reynaudi*
[43] *S. fusiformis* / *S. maxima*

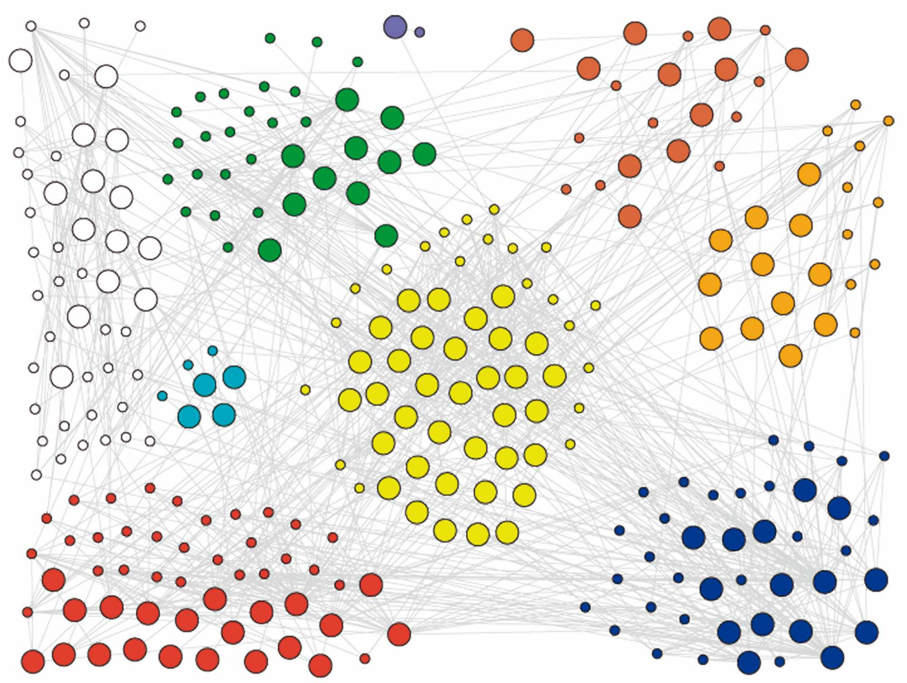


Figure 5: The fishing events and by-catch species network of the small-scale fisheries fleet of port of Palamós, showing the modular structure. Colours correspond to the nine modules: M0 (white), M1 (violet), M2 (orange), M3 (yellow), M4 (green), M5 (turquoise), M6 (red), M7 (blue) and M8 (brown). In each case, small circles represent fishing events and large circles represent species. Links (black lines) are defined by the occurrence of a species in a fishing event. See Tables 6 and 7 for a detailed modules composition. The spatial arrangement of modules in the plot is arbitrary.

Module 0 (45 fishing events and 23 species) was characterized by fish species such as *Chromis chromis*, *Diplodus sargus*, *Diplodus vulgaris*, *Conger conger*, and *Oblada melanura*. This module was primarily associated with octopus pots (OP) and a maximum depth of 30 m. Module 1 (1 fishing events and 1 species) was composed only by *Polyodontes maxillosus* and was related with bottom long-line (BL). Module 2 (10 fishing events and 13 species) was characterized by species such as *Auxis rochei*, *Liza ramada*, *Myliobatis aquila* and *Rhizostoma pulmo* among others. This module had no clear relationship with any of the gears and fishing events occurred mainly at a depth of 50 m. Module 3 (21 fishing events and 35 species) was characterized by species such as *Alcyonium acaule, Smittina cervicornis, Leptogorgia sarmentosa* and *Paramuricea spp*.

among others. Trammel nets (TN) were dominant, and fishing operations took place in a range depth of 11 to 109 m. Module 4 (13 fishing events and 11 species) was comprised by species such as *Myriapora truncata*, *Paracentrotus livid*us, *Dardanus calidus* and *Cotylorhiza tuberculata* among others. Like the module 2, this module does not present a clear association with any of the fish gear. Module 5 (3 fishing events and 4 species) was characterized only by fish species (*Dentex dentex*, *Liza aurata*, *Sarda sarda* and *Scomber japonicus*) and was primarily associated with gillnet (G) at depth between 5 to 42 m. Module 6 (21 fishing events and 12 species) included e.g. *Bothus podas*, *Calappa granulata*, *Raja asterias*, *Sphyraena sphyraena* and *Spondyliosoma cantharus* among others. This module was also associated with trammel and gillnets and a range depth to 5 – 109 m. Module 7 included *Astropecten aranciacus*, *Halocynthia papillosa*, *Ophioderma longicaudum*, *Turritella turbona* among others. Bottom long-lines were the most used fishing gear (68%) in bottoms ranging from 9.3 to 90.3 m. Module 8 (10 fishing events and 11 species) was characterized by species such as *Pennatula rubra*, *Loligo vulgaris*, *Raja undulata*, *Sardinella aurita* among others. This module was also associated with beach seine (BS) and a maximum depth of 25 m. The characteristics of these modules and the species are presented in figures 5, 6 and 7 and tables 5 and 6.

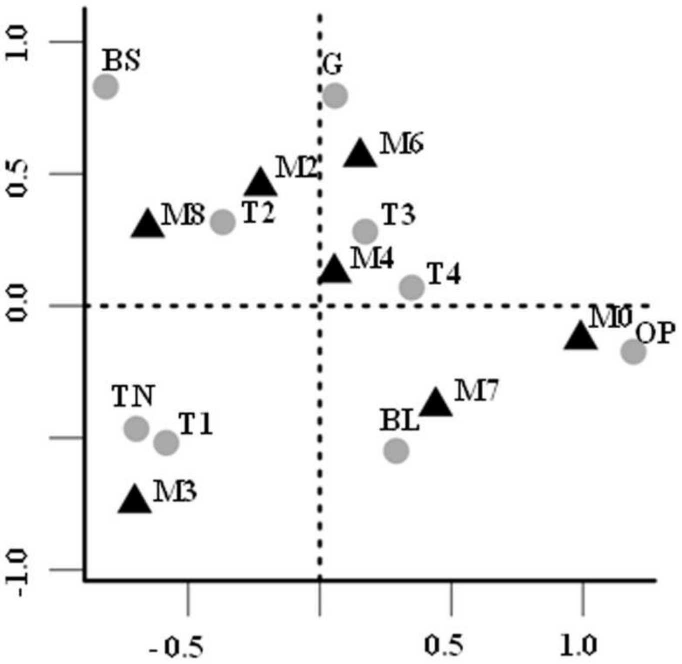


Figure 6: Correspondence analysis (CA) to visualize module composition. Only module 0 (M0), module 3 (M3) and module 7 (M7) could be explained by species type and/or gear. T1, T2, T3 and T4 correspond to the classification proposed by Orensanz and Jamieson (1998). Gears are as follow: BL: bottom long-line, G: gillnet, BS: beach seine, TN: trammel net and OP: octopus pots.

3.3 Temporal trends in the small-scale fisheries of Palamós

The most striking trend in the data series was a peak in LPI_{FE} and LPI_{FP} observed in 2008. This peak coincides with an absolute minimum from the study period concerning total landings. However, when figures from 2008 were removed, was unveiled a strong significant negative trend for LPI_{FP}, significantly and negatively correlated with year. The same holds true for LPI_{FE} and LPI_{DEB} (Figure 8). Further, all variables were strongly and positively correlated, always with Pearson's $R > 0.84$ (Table 8).

Finally, autocorrelation analysis revealed that interannual changes for each of the three response variables were serially independent. Sample autocorrelation indicates no autocorrelation of the regression residuals for LPI_{FP} vs. LPI_{FE} (Durbin-Watson d = 1.94) and for LPI_{DEB} vs. LPI_{FE} (d = 1.80). However, the sample autocorrelation for the bivariate relationship LPI_{FP} vs. LPI_{DEB} (d = 3.11) suggested that successive error terms are, on average, much different in value from one another, i.e. negatively correlated. In regressions, this can imply an underestimation of the level of statistical significance for the bivariate relationship between LPI_{FP} and LPI_{DEB}, and thus the observed p-value (0.04) would mostly likely indicate a fairly strong correlation.

Table 8: Correlation analysis among variables used to evaluate trends in the multispecies small-scale fishery of Palamós Marked correlations (*) are significant at $p < 0.05$ (N=8). LPI_{FE}: LPI for Fishing Effort, LPI_{FP}: LPI for Fish Populations and LPI_{DEB}: LPI for Direct Economic Benefits

	LPI_{FE}	LPI_{FP}	LPI_{DEB}	Year
LPI_{FE}	1.0			
LPI_{FP}	0.88*	1.0		
LPI_{DEB}	0.88*	0.89*	1.0	
Year	-0.74*	-0.93*	-0.84	1.0

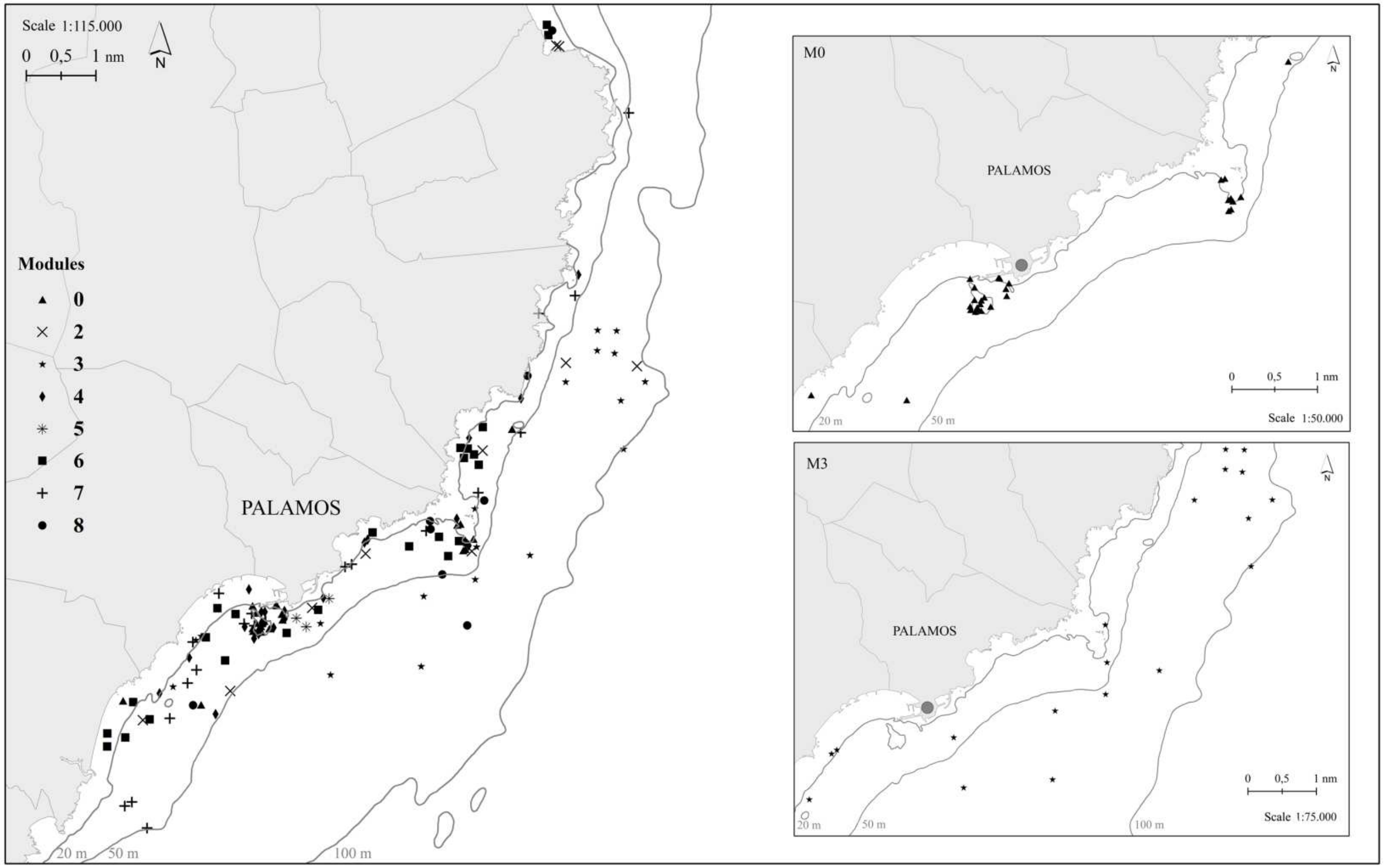


Figure 7: Spatial distribution area of the small-scale fisheries fleet of port of Palamós showing the allocation of modules. Panels on the right correspond to the spatial distribution of modules 0 (M0) and module 3 (M3).

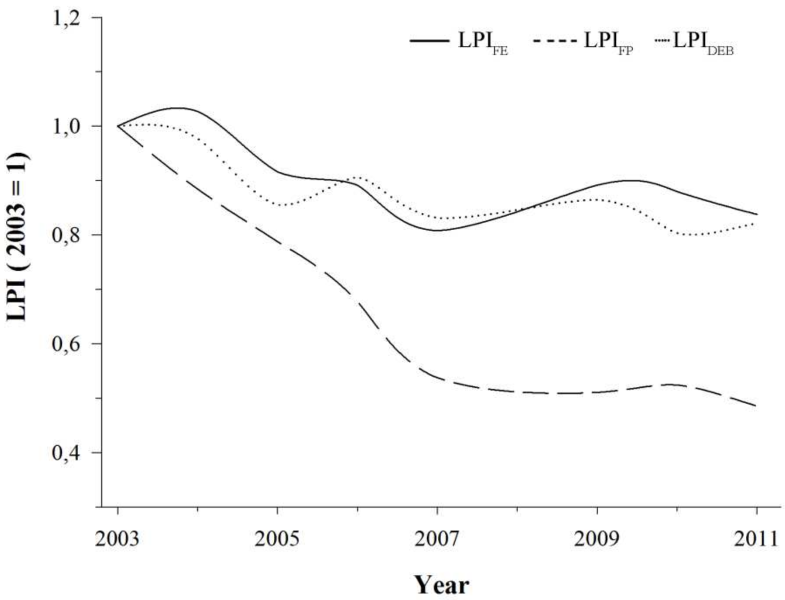


Figure 8: LPI trajectories for fishing effort (LPI_{FE}), fish populations (LPI_{FP}), and direct economic benefits (LPI_{DEB}). The lines represent the observed trend calculated with 36 species.

3.4 Histological assessment of gonad development and sexual cycle of Pagellus erythrinus

3.4.1 Sex identification, sex reversal and maturation stages

Primary males of common pandora directly develop from immature fish and secondary males from females through sex change. The histological examination of the 126 specimens showed the following gonadal differentiations: functional ovaries without male tissue (F), functional testis without female tissue (M), ovotestes with inactive ovary and growing testis (fm) and ovotestes with functional testis and regressed ovary (fM). Two individuals (1.6% of the sample) could not be classified because their gonads were barely visible as thin filaments adhered to the abdominal wall, being not possible to prepare suitable paraffin blocs.

The differentiated gonadal types: M, F, fm and fM, occurred in the overall ratio of 7.3%, 47.6%, 8.9% and 35.5%, respectively. Secondary males were found all along the year, and intersexual individuals (fm) in different size classes throughout the year, except during the months of January, February, June and July. Based on these results, was established a hypothetical sequence of different stages of sexual differentiation for common pandora (Figure 9).

Primary males (M)

The testes of primary males (M) were denser than ovaries and were round shaped in cross-section. They ranged in colour from white to milky yellow, according to their stage of maturity. Microscopically, they were unrestricted lobular, showing spermatogonial development along the germinal epithelium of the seminiferous lobules in reproductively active fish. These lobules converge to form the efferent ducts (ED) at the testis periphery (Figure 10a).

Functional ovaries (F)

The functional ovaries of females (F) were oval-shaped, displaying two lobes that were fused posteriorly, and suspended from the dorsal abdominal wall by a thin mesovarium. They were of the cystovarian type, that is, it contains a lumen or ovarian cavity into which eggs are released during ovulation. The ovarian lamellae, containing the developing oocytes, extent from the ovarian wall to the central lumen or cavity. Macroscopically immature ovaries were tubular and filamentous organs and transparent. The ripe ovaries become larger and opaque with a pink to orange colour depending on the maturity stage (Figure 10b).

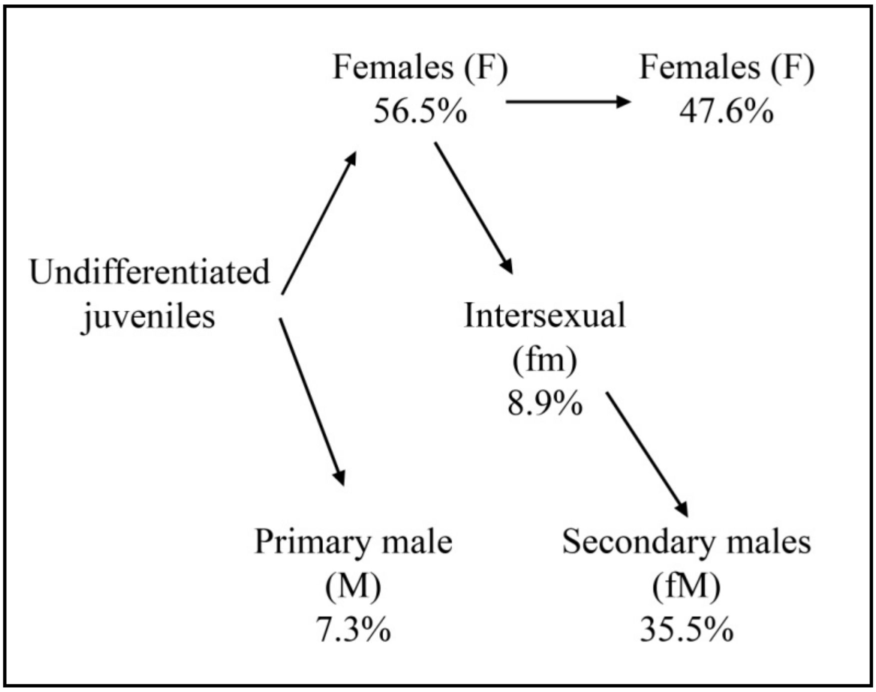


Figure 9: Hypothesized sequence for sex differentiation in wild *P. erythrinus*, and percentage of each stage obtained through histological analysis.

Histological examination of the ovaries revealed an asynchronous development of the oocytes, with all the stages of oogenesis being evident during the spawning season (Figure 10b). Secondary growth oocytes started with the cortical alveoli stage, which organized at the periphery of the ooplasm. Nearly at the same time, oil droplets appeared near the nucleus. The vitellogenesis began when the yolk globules appeared and progressively increased in number and volume. At this time, oocytes grew rapidly in volume with the accumulation of yolk and yolk globules eventually occupying all the cytoplasm. The nucleus remained located at the centre during the vitellogenesis phase (Figure 10b). At the final maturation phase, lipid droplets merged into a large droplet at the centre of oocyte, and the germinal vesicle (nucleus) began its migration to the animal pole. There was no evidence of development of male tissue and efferent duct differentiation in any of the female gonads analyzed.

Intersexual individuals (fm)

Even intersexual individuals were not macroscopic easily recognised; they were clearly identified via histological examination. Morphologically, these ovotestes were typically ovarian in form, with developing lamellae, but just presenting oocytes in the primary growth (Figure 10c and 11a-d). The analyzed gonads of these individuals presented different levels of development towards sex change. This allowed us to describe female to male sex-change process (Figure 11). In a first stage, was observed slit-like structures in the ovarian wall and small oval-shaped spaces appeared which develop as spermatogonial nests (Figure 11a), then testicular tissue proliferates from this spermatogonial nests in the ovarian wall (Figure 11b-d). Both tissues, ovarian and testicular, were separated from one another by connective tissue and the spermatogonial cysts were observed growing at the same time of a thickening of the ovarian wall in its ventral region. Testicular tissue proliferated progressively in this area and new efferent ducts developed in the inner part of the testicular tissue (Figure 11f).

Secondary males (fM)

Testes of males which had recently changed sex, or secondary males (fM), differed morphologically of primary males (M) (Figure 10d). Macroscopically the testis of secondary males (fM) was characterized by two lobes which developed from the ventro-lateral area of the ovary, extending from the posterior portion of the ovary forward. These testes are more triangular shaped (Figure 11f-h). The structure of the testis as a secondary male has a lamellar structure, and efferent sperm ducts are situated at the inner part of the testis, filled with mature sperm (Figure 11g). A remnant of the membrane bond ovarian cavity or lumen, is more or less present (Figure 11e-g). There is no evidence that the sperm is released to the ovarian lumen, but in fact, a main spermatic duct is finally observed at the centre of the gonad after the convergence of the efferent ducts, and occupies the area where the ovarian lumen was previous situated (Figure 11g-h). In each one of these gonads spermatogenesis was active, and a simultaneous degeneration of previtellogenic oocytes and ovigerous lamellae in the ovary was observed. The prevalence of eosinophilic cells and melano-macrophage centers in the secondary male with recent sex-change could indicate a relationship between that cell type and the sex change process (Figure 11b-h). Likewise, 82% of the secondary males showed melano-macrophage centers.

3.4.2 Cross-validation of morphological and histological sex determination

Although sex determination based on the external characteristics of gonads seemed very obvious for common pandora, 47.6% of the 124 gonads were misclassified by this method. The most common mistake (59.3% of cases) occurred in sorting primary males (M) from secondary males (fM), besides, 5 secondary males (fM) and 10 intersexual (fm) gonads were classified as females (F) and, 15 gonads were classified as females (F), actually being 5 secondary males and 10 intersexual gonads.

3.4.3 Population parameters

The reproductive cycle of the common pandora based on frequencies of the reproductive phases and the variation of mean GSI values was assessed. The evolution of the mature reproductive stages throughout the year seems to evidence that the reproductive period starts in February and extends up to August. Spawning females (F) show a peak in May while primary males (M) in June (Figure 12a and b). Secondary males (fM) were observed in spawning capable and actively spawning throughout the year without showing a clear pattern of reproductive activity (Figure 12c).

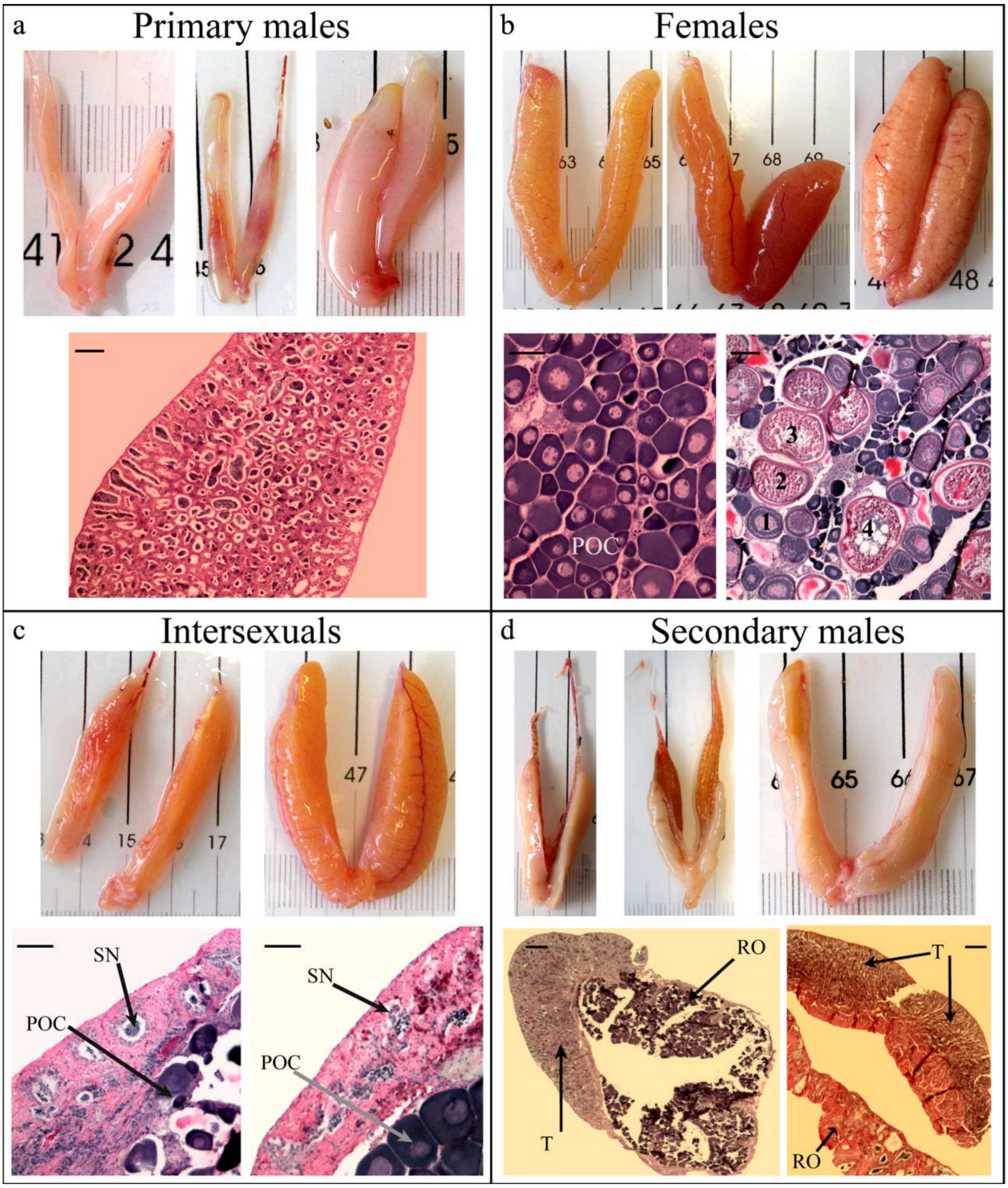


Figure 10: Reproductive protogynous hermaphroditism for different types of gonads found in *P. erythrinus*. Scale bar, a) 100 µm, b) 50 µm and 100 µm, c) 50 µm and d) 250 µm. POC: primary growth oocytes, RO: regressing ovary, SN: spermatogonial nests, T: testicle, 1: early vitellogenic oocytes, 2: advanced vitellogenic oocytes, 3: vitellogenic oocytes with yolk and lipid droplets and 4: lipid droplets.

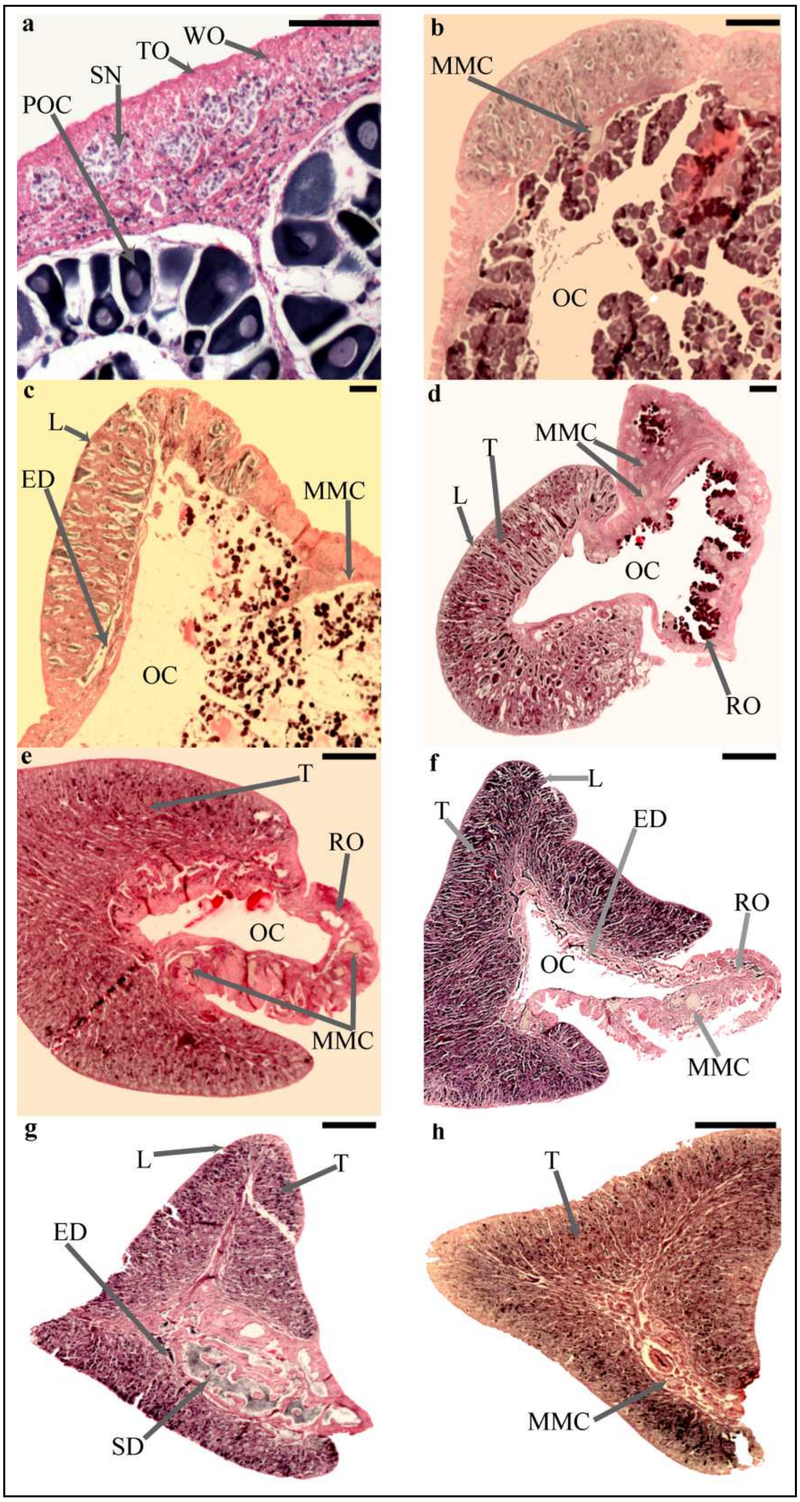


Figure 11: Process of natural sex change in wild *Pagellus erythrinus*. O: ovary, TO: tunica ovary, WO: wall of ovarian, OC: ovarian cavity, RO: regressing ovary, POC: primary growth oocytes, T: testicle, L: lobules, SN: spermatogonial nests, SD: sperm duct, ED: efferent ducts, MMC: melano-macrophage centers. Scale bars, a) 50 μm and b-h) 250 μm.

The analysis of GSI variations throughout the year showed a similar general pattern of reproductive activity for females (F) and primary males (M) and showed a different pattern for the secondary males (fM) (Figure 13a). Mean GSI values for female (F), primary males (M) and secondary males (fM) showed a peak of reproductive activity mainly during May and June (Figure 13a). Significant differences in the monthly GSI values were detected only for females (F) (Kruskall-Wallis: $H = 24.654$; $p < 0.05$). Dunn´s Test identified two distinct groups of females (F) over the year. One group with higher GSI values occurring from April to July and the other, with lower GSI values, from September to March.

Mean GSI values were also assessed considering maturity stages. Mean value for females (F) during spawning capable and actively spawning phases were 2.33 ± 1.78% and 3.67 ± 1.25% respectively (Figure 13b). During these phases, the mean GSI values were higher for primary males (M) than for secondary males (fM) (0.851±1.08% and 1.45±0.50% for M and 0.37±0.31% and 0.70±0.58% for fM).

The relative distribution of differentiated gonadal types per size classes is presented in figure 14. Primary males (M) only was found in individuals between 18.0 cm and 26.0 cm length with a mean size of 22.3 ± 2.6 cm. Female (F) occurred in all size classes and presented a mean size of 26.4 ± 6.0 cm. Intersexual individuals (fm) were most frequent between 28.0cm and 39.0 cm with a mean size of 30.6 ± 5.3 cm., while secondary males (fM) were predominant in larger sizes with a mean size of 31.7 ± 4.0 cm.

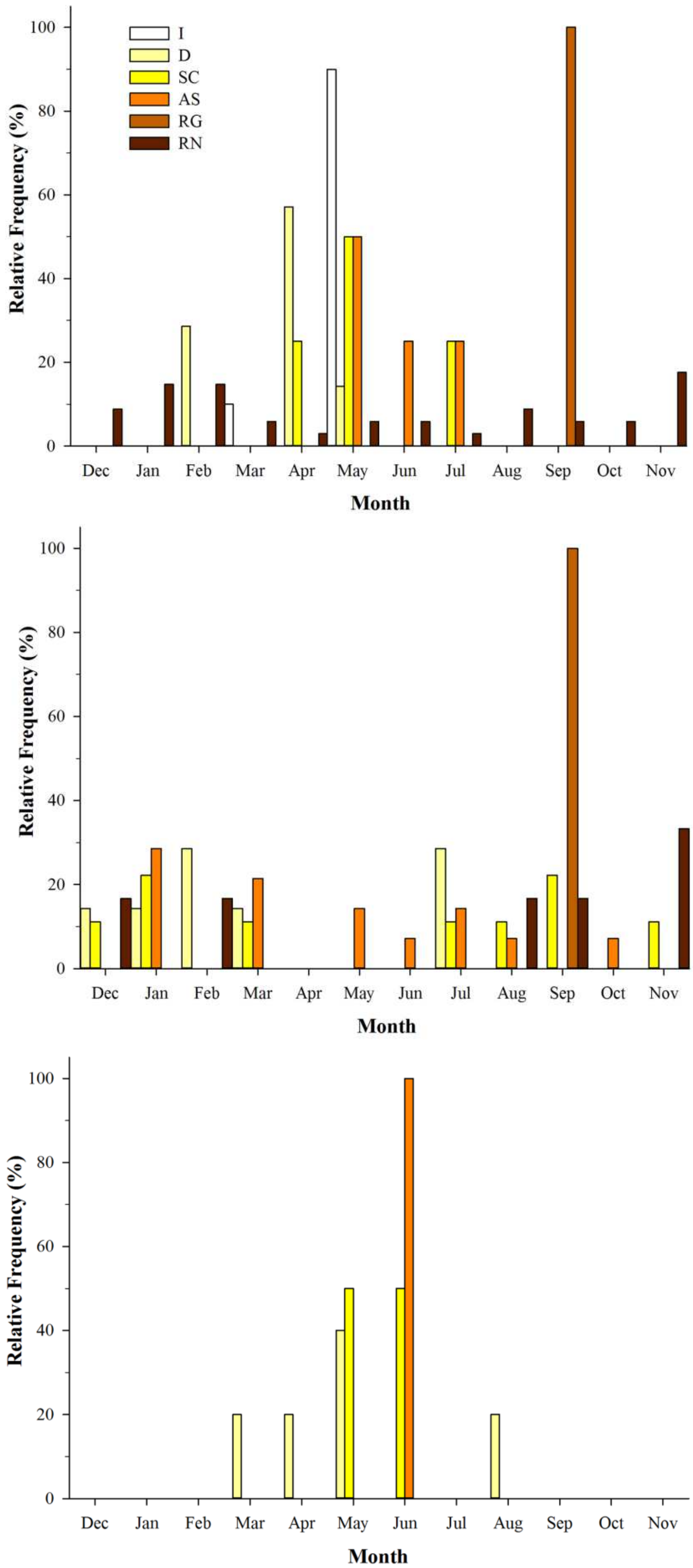


Figure 12: Monthly evolution of the relative frequency for mature stages in females (a), primary males (b) and secondary males (c) of *P. erythrinus*. I: immature, D: developing, SC: spawning capable, AS: actively spawning, RG: regressing and RN: regenerating.

The total length of secondary males (fM) was significantly higher than the ones of females (F) and primary males (M) (Kruskall-Wallis: H = 28.107, $p < 0.05$; Dunn´s Test: -33.673, $p < 0.05$; Dunn´s Test: -59.828, $p < 0.05$), while the total length of intersexual (fm) was significantly higher than primary males (Kruskall-Wallis: H = 28.107, $p < 0.05$; Dunn´s Test: -52.646, $p < 0.05$). The overall ratio between females and males (M+fM) was 1.13:1 was not significantly different (n= 113; $\chi^2 = 0.43 < \chi^2_{t1,0.05} = 3.84$).

The smallest observed female was 15.5 cm length, while the smallest observed male achieved 18.0 cm length. For females the size at which 50% of the population is mature, was estimated at 19.3 cm (IC 95%: 17.7 - 21.0 cm, a = -13.09 ± 4.36, b = 0.68 ± 0.23, R^2 = 0.847), however, because no primary immature males (M) were observed, it was not possible to determine the size at first maturity for males. The sex inversion was estimated at 33.3 cm (IC 95%: 30.9 – 35.7, a = -8.378, b = 0.263, $p < 0.0001$).

3.4.4 Fisheries Data

According to the data recorded by the fishermen guild of Palamós, 62.8 t of common pandora were caught by the small-scale fleet from 2002 to 2011. The most striking trend in the data series was a peak in the LPI_{FE} and LPI_{TL} indices observed during 2008 (Figure 15). Ordinary least square regression showed significant trend and positive associations between LPI_{FE} and for total annual landings (LPI_{TL}; $r^2 = 0.528$; p = 0.027). Both variables were not correlated with year. In this period, catches were higher from December to June (ca. 6.5 t), while the lowest catch was recorded in October (2.2 t).

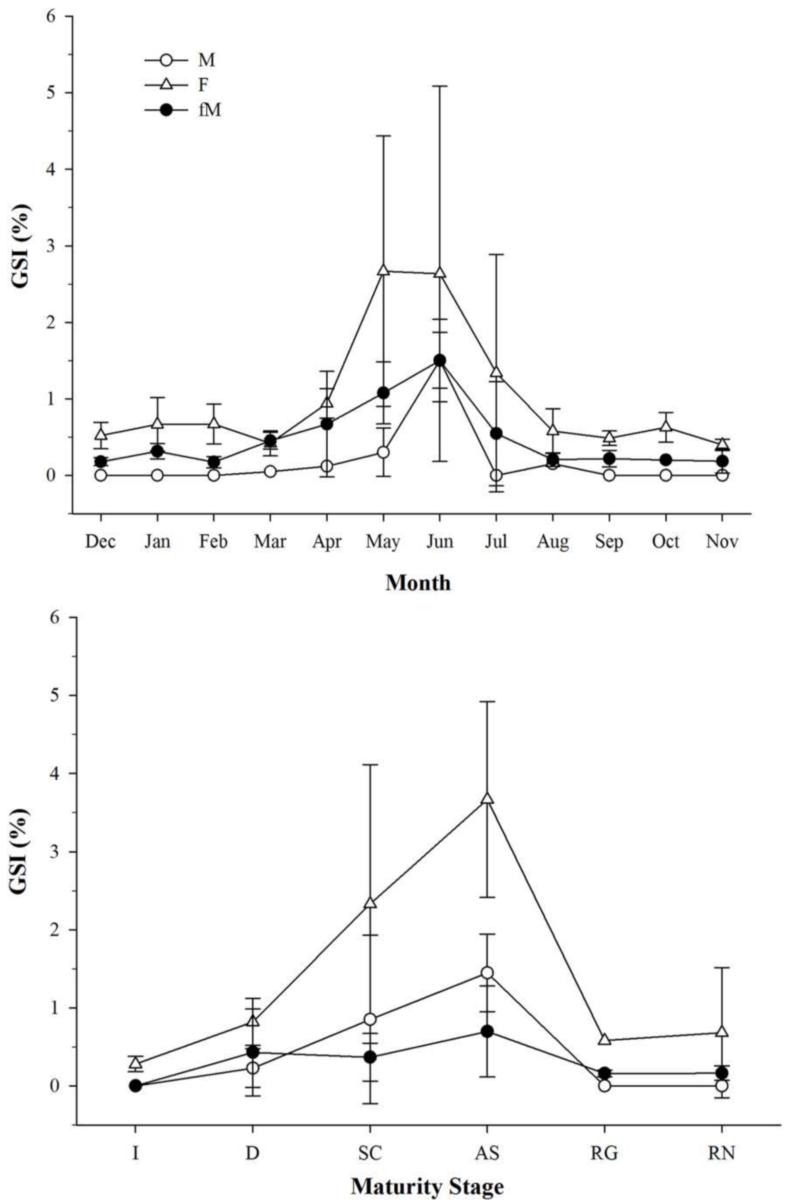


Figure 13: a) Monthly evolution of the gonadosomatic index (GSI, mean ± SD) and b) evolution of the gonadosomatic index (GSI, mean ± SD) according to the state of maturity for *P. erythrinus*. Females (F), primary males (M), secondary males (fM), I: immature, D: developing, SC: spawning capable, AS: actively spawning, RG: regressing and RN: regenerating.

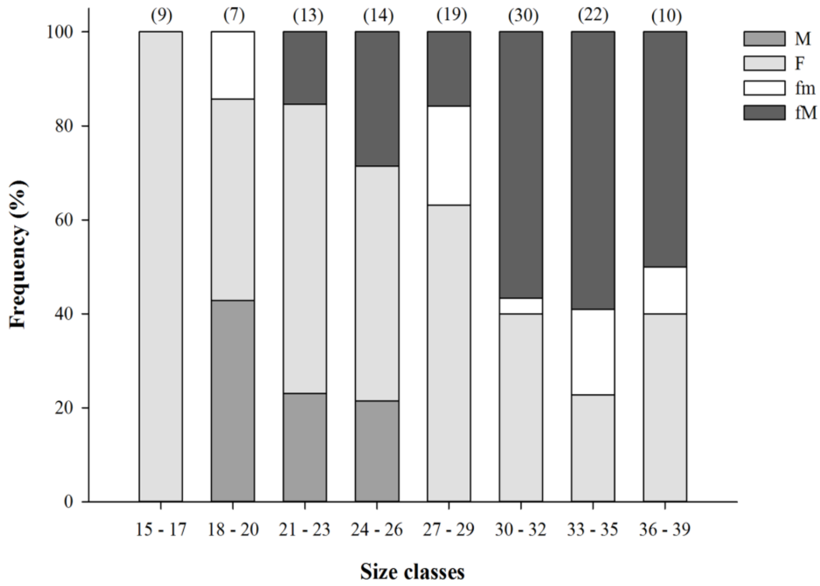


Figure 14: Size-frequency distribution of differentiated gonadal types of *P. erythrinus*. Sample sizes are indicated above columns. F: females, M: primary males, fm: intersexual, fM: secondary males.

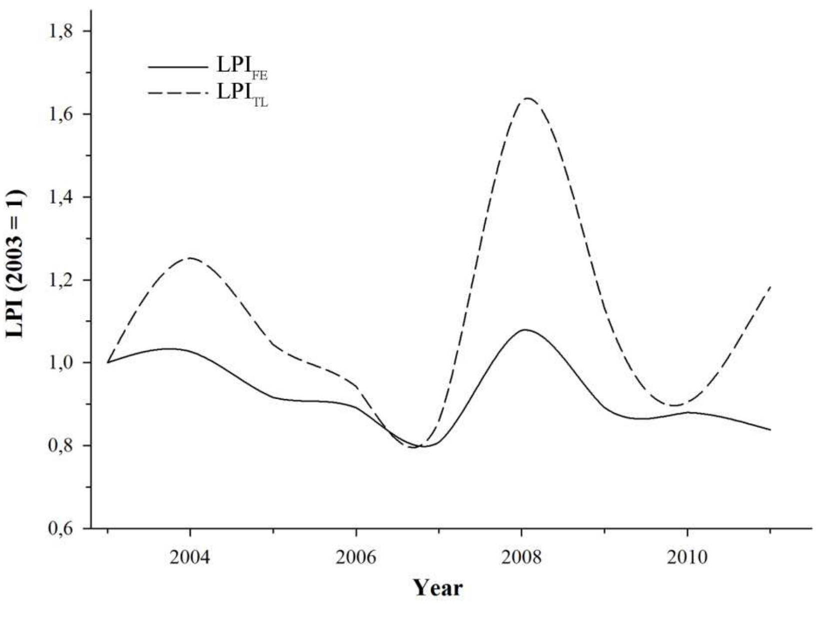


Figure 15: Living Planet Index (LPI) trajectories for fishing effort (LPI_{FE}) and total landing (LPI_{TL}) for *P. erythrinus* estimated from the total landed small-scale fisheries of Palamós Port (Data from Fisheries Guild 2003 – 2011).

From 203 fishing events observed, 55.1% of common pandora was caught using the bottom long-line fishing technique, followed by the beach seine and gillnet (achieving 31.4% and 9.8% of the total catch, respectively). Octopus pots were the only fishing gear in which no catch of this species was recorded. Given the low recorded catches of common pandora in trammel nets and octopus pots, only the data from the bottom long-line, gillnet and beach seine were considered for the analysis (Table 9).

The bottom long line fishing grounds' depth varied between 9.3 m and 90.3 m. Usually, this gear targets multiple species during a single fishing event and a typical fishing operation involves the use of between 100 and 1100 hooks placed every 8 ±3m, during a time period that can vary from1.5 h to 26.5 h. The hooks were baited by hand with hermit crabs (*Dardanus sp*.), shrimp (*Aristeus antennatus*) and sepia (*Sepiola rondeleti*) depending on availability, price and target species.

Gillnets also targeted multiple species in a depth range between 5.0 m and 42.0 m. Although was observed the use of several mesh sizes, 69.4% of gillnet fishing events used a mesh size of 80.0 mm. Fishing operations lasted from 13.9 h to 24.9 h, being the average total length of the gear 650 ± 156 m.

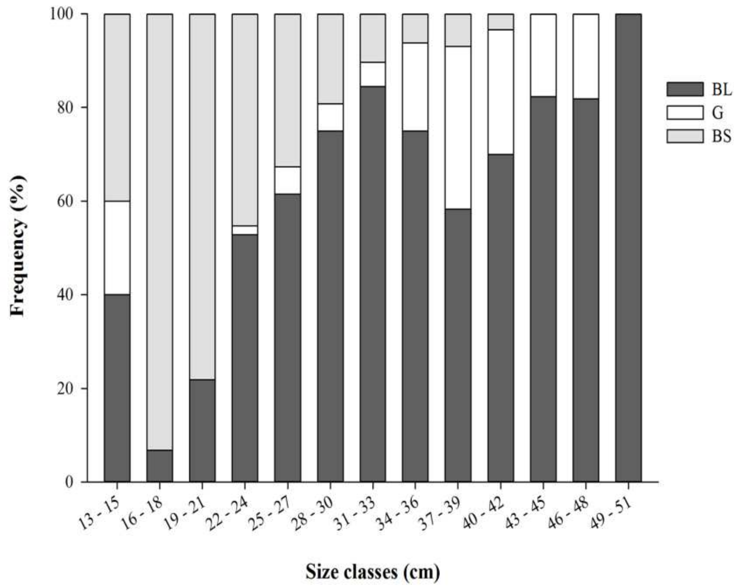
Beach seine gear usually operated on sandy bottoms less than 23 m depth and targeting sand eel (*Gymnamodytes sp).* By-catch species with commercial value (e.g. common pandora) were usually sold and others remained for subsistence, while fish below the minimum landing size were discarded.

Table 9: Fishing events with captures of *P. erythrinus* detailed for each registered fishing gear (BL: bottom long line, G: gillnets, BS: beach seine, FTN: fish trammel nets, LTN: lobster trammel nets and OP: octopus pots), MSC: mean catch sizes. * Abundance of *Gymnamodytes sp*. was not considered.

Total Sampling Data			*P. erythrinus* Data			
Gear type	Fishing events	Total catch (%)	Catch (%)	MSC ± SD (cm)	IC 95%	Sizes range (cm)
BL	37	45.7	21.3	32,7 ± 6,9	31.9 – 33.9	13 - 51
G	36	17.4	14.2	36,5 ± 5,6	35.0 – 37.9	14 - 48
BS	18	2.9*	75.1	22,4 ± 5,9	21.5 – 23.4	15 - 40
FTN	30	20.3	2.0	29,7 ± 2,4	28.5 – 30.8	23 - 34
LTN	22	6.5	2.5	34,5 ± 11,2	16.7 – 52.3	26 - 51
OP	60	7.9	0.0	-	-	-
Total	203	1.6 ton	0.24 ton	30,2 ± 8,1	-	13 - 51

The beach-seine consisted of a 115 m length and 8 m depth netting wall, with an upper float line and a lower sinker line. The cod-end was 10 m to length and the opening of the mouth was between 7 m and10 m to width.

Significant differences were observed in the size of individuals captured by the various fishing gears (Kruskal - Wallis: $H = 194.385$, $p < 0.05$). Both, gillnet as bottom long line fishing techniques, captured individuals of larger sizes (MCS: 36.5 ± 5.6 cm and 32.7 ± 6.9 cm, respectively), while the smaller individuals were captured with the beach seine (MCS: 22.4 ± 5.9 cm) (Figure 16a). For the study period, the size range of caught individuals was comprised between 13.0 cm and 51.0 cm TL (Table 9). The size of the 15% of the individuals caught by the small-scale fleet was below the L_{50} limit for females (19.3 cm). Furthermore, 41.8% of caught individuals were larger than the sex change size estimated by this study (33.3 cm) (Figure 16b).



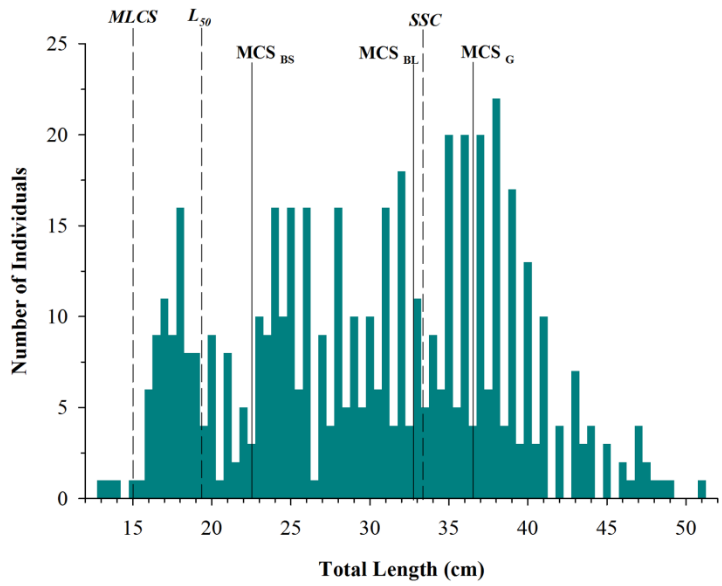


Figure 16: Length frequency of *P. erythrinus* in Palamós small-scale fishery during the period 2010-2012, a) by fishing gear and b) lengths frequency. BS: beach seine, BL: bottom long line, G: gillnets, MLCS: minimum length catch size, L_{50}: mean size at sexual maturity for females, SSC: size at sex change, MCS: mean catch size.

CHAPTER 4

DISCUSSION

4.1Monitoring small-scale fisheries towards Aichi targets

This thesis exposes a specific example of usage of landing declaration data and fishing effort to build an indicator of fisheries' performance, based on the Living Planet Index (LPI). This index is being increasingly used for monitoring wildlife population across the globe (Loh *et al*., 2005; Collen *et al*., 2009, 2011, 2013; Galewski *et al*., 2011; Di Fonzo *et al*., 2013; Tittensor *et al*., 2014), but up to date it has not been applied to monitor fisheries. It emphasizes the adaptability of the index to self-declared landing data. This method is a quick and cost-effective technique for assessing biodiversity change in short time-lags commonly related between human pressures and corresponding shifts in population trends (Di Fonzo *et al*., 2013). However, caution may be taken when interpreting the trends depicted by the LPI in a socio-ecological system such as commercial fisheries, since trends in the indicators may be reflecting the operation of both ecological and socio-economic drivers. Further, and as for other indicators, the trends shown by the LPI depends on data quality, changes in data gathering procedures that are not fully documented, or other gaps in comparability that have not been detected. The index trends may also mask important trends in individual populations or particular groups of species, a fact that was acknowledge and will be discussed below.

The Port of Palamós harbours a multi-specific SSF, landing ca. 130 species, ca.15% of these of special interest for fisheries, biodiversity conservation, and/or in urgent need for research and can be considered representative of SSF in the NW Mediterranean. Raw data showed an uni-modal response in LPI_{FP}, owing to unusual values for 2008. Here, positive changes were observed in the landings of some species, namely squids

Omastrepidae, the small pelagic fish *Micromesistius poutossou*, *Trachurus spp*., *Gymnammodytes spp*., *Lophius spp*., and *Citharus linguatula*. *Gymnammodytes spp*. and *Lophius spp*. being the exception, all these species were of lesser commercial interest. However, after outlier removal, the general trend is negative, showing a decrease in LPI_{FP} across the time-series. Thus, the negative trend in LPI_{FP}, while analysed jointly with the slight decrease observed in the LPI_{FE} could be indicating a decreasing socio-ecological sustainability of this fishery. This is in agreement with the perception of local fishermen, which claimed that there was a significant decline in catches in recent years. In this line, in 2008 and with the support of local scientists, fishermen requested the establishment of a Marine Protected Area (MPA) to protect the fishing grounds (Chuenpagdee *et al*., 2013).

Theoretical schemes depicting different socio-economical scenarios are shown in Figure 17 to generate a framework for the interpretation of observed trajectories of the LPI considering trends in fishing effort, trends in fish populations and trends in direct economic benefits. The observed trend in LPI_{DEB} is not included in this model to avoid unnecessary complexity, but it should be taken into consideration that for each given scenario there are three possible configurations (e.g. stationary, growing, or decreasing DEB). From a purely economical standpoint, a desirable or positive scenario can be depicted if one DEB is positively correlated with fishing effort, given that the trends in fish populations are stable or growing. Otherwise, it may highlight a positive, short term economic benefit but no ecological sustainability. In short, Figure 17a and b depicts positive scenarios, likely indicating an ecological sustainability of the fisheries. Conversely, Figure 17c and d illustrates non-desirable scenarios, leading in extreme cases to overexploitation, and subsequent fisheries collapse if management actions are not taken. According to the model presented in this thesis, and despite the slight decrease in LPI_{FE}, the case of the SSF in Palamós is similar to scenario 17c, thus highlighting the needs for improving the management of this fishery.

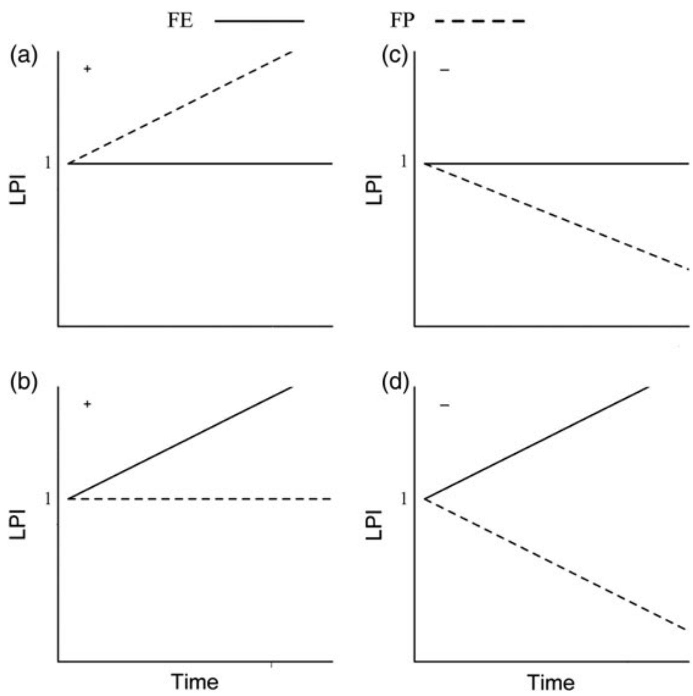


Figure 17: Theoretical scenarios relation trends in LPI trajectories for fishing effort (FE), and fish populations (FP). (a) and (b) Positive trends in FP with either increasing or constant FE, and thus are indicating well. (c) and (d) A negative scenario, with decreasing FP under constant FE (negative biodiversity impacts) and increasing FE (both negative biodiversity and economical impacts), indicating a likely overexploitation of fish stocks and subsequent fisheries collapse.

In this line, available evidence indicates that fish populations in the NW Mediterranean Sea are rapidly declining in abundance as a consequence of combination of threats, worsened by its enclosed nature and the particularly intense fishing activity, both in its coastal and pelagic waters (Aldebert, 1997; Walker *et al.*, 2005). This poses a serious threat in relation to ABT. Furthermore, few effective protection measures are currently in place, either for species or ecosystems (Bianchi and Morri, 2000), and rapid urban and industrial development and associated pollution have degraded critical coastal habitats, such as fish nursery and spawning areas (Camhi *et al*., 1998; UNEPMAP /RAC/SPA, 2003; Stevens *et al*., 2005).

The analysis of general trends should be ideally complemented with other quantitative (e.g. size-frequency distributions) and qualitative (e.g. reproductive status) data on individual fish species. In agreement with this, in this thesis also unveiled significant changes in catch composition for the study period, compared with data from 1982 (Alegret, 1987) when the main species landed were *Conger conger* (20781 kg), *Gymnammodytes cicerelus* (10691 kg), and *Scyliorhinus canicula* (9546 kg). Considering the top 10 species in terms of landed biomass (kg), only 30% of those landed in 1982 are found in this study. For our study period, *Gymnammodytes spp*. was the dominant species in the fishery. This change may be associated with the increase in the number of boats arrived to the Catalonian coast in recent years, and the 5-fold increase in market price for the species (Lleonart *et al*., 2014). Since 2012 a Sandeel Co-Management Committee was formally created with the specific mission of ensuring a sustainable fishery (*Gymanammodytes cicerelus* and *G. semisquamatus*) in accordance with EU rules (Lleonart *et al*., 2014).

The hake *Merluccius merluccius* is another example of increased catches. This species, currently ranked second in terms of biomass landed (10% of total catch), was only a minor component of the ones recorded in 1982 (Alegret, 1987). This may be related to the implementation of bottom long lines since the mid-1980s and the use of sonar, causing a significant change in the evolution of the fishery (Martínez and Casadevall, 1997). While *Conger conger* catches have declined over time, it still remains as one of the species most commonly traded in the auction. In contrast, catches of species such as *Scyliorhinus canicula* have decreased due to low market demand; being actually uncommon in the auction sales' records. These examples highlight the need for considering the socio-economical scenarios beyond pure ecological drivers of the observed trends to understand key components of fishery dynamics.

At national or regional levels, fishing authorities could integrate the LPI approach to fisheries, treating individual ports or fisheries as species or populations following the LPI guidance. In this context, each individual fishery can be weighted following specific standard criteria, such as the percentage of species of special interest. In this vein, species listed as LC at the regional scale are about a half of those listed as such at a global scale, highlighting regional issues on the conservation of these species. Thus, it suggests the use of regional IUCN assessments, when available. Besides the IUCN, there are a number of other assessments that can be combined or used alternatively to rank fisheries. In fact, relatively few of the species currently listed in the IUCN threatened categories have been listed under any relevant conventions, and thus such approach may be more comprehensive. For example, the swordfish *Xiphias gladius* is listed in Annex III of the Barcelona Convention, the North Atlantic stock of that species is listed as Endangered by IUCN, and the Mediterranean stock is considered to be among the worst managed. However, the species is still listed as Least Concern (Safina, 1996).

At a continental level, the European Commission developed the Marine Strategy Framework Directive (MSFD) for the protection and sustainable use of marine ecosystems. The MSFD builds on sector-based approaches such as the Common Fisheries Policy (CFP), Natura 2000, and the Nitrates Directive. The MSFD establishes a framework within which Member States must take action to achieve or maintain Good Environmental Status (GES) for the marine environment by 2020 (EC, 2008). Thus, knowledge of the status and trends of fisheries' catches, including socio-economic aspects, is a key aspect to sound development of policies, better decision making, and responsible fisheries management (de Graaf *et al*., 2011). In this context, the LPI approach to fisheries can be adopted by the MSFD to identify priority fisheries to allocate conservation and/or management resources, targeting either species or ecosystems. These should ideally follow schemes of decentralized management, including co-management, and the ecosystem approach to fisheries (EAF) (e.g. Chuenpagdee and Jentoft, 2007; Berghöfer *et al*., 2008).

Although limited data availability and/or quality are often mentioned as a problem, as is true in the analysed fishery, this argument should not preclude the use of this information. The primary purpose behind collecting, compiling, and analysing capture-fishery statistics should be to support regional, national, and local decision making in policy development, sectoral planning, and fishery management, to inform decision making towards the consecution of global biodiversity targets.

4.2 A network approach to by-catch

In this thesis, was shown how a network approach to fisheries can be used to identify non-trivial units within the socio-ecological system, which depicts a combination of fishing events and by-catch species, thereby allowing managers to focus on unknown or foreseen interactions among fishing gears and species, assemblages or communities. In this line, this is the first time that a modularity analysis is applied in fisheries science.

According to the modularity analysis, nine discrete groups (modules) are present in the bipartite network under study. Two modules comprise single or few fishing events and species (i.e., a fortuitous by-catch of “rare” species). As such, and since the objective of this work is to seek for generality, these are no further explored. The remaining seven individual modules include, however, non-negligible number of fishing events and species, ranging from 6 to 20% and 8 to 28% respectively. Thus, in quantitative terms, all these modules may be of interest to a fisheries manager. However, this quantitative approach should be complemented with a close look at the identity, ecology and socio-economical relevance of species (conservation status, fisheries value, etc.) and the fisheries context (i.e., gear used, target species) within each module, aided by the post-hoc explanatory analysis performed by means of the Correspondence Analysis.

Of the modules here identified, module 3 is perhaps the most interesting. Since was unveiled a significant association between trammel nets and biogenic habitats, is worth further analysing. Trammel nets are usually deployed close to rocky bottoms, typically with high diversity of habitat-forming species, and may thus reduce habitat complexity (Voultsiadou *et al*., 2011). Some studies have shown that impacts of trammel nets on habitats are non negligible, and seem to affect particularly the fragile, sessile animals of the coralligenous assemblages (Tudela, 2004; Gonçalves *et al*., 2008; Batista *et al*., 2009; Voultsiadou *et al*., 2011). Accordingly, in Module 3, there is predominance of benthic species type 1 (sessile regenerating invertebrates), most endemic or with limited ranges (e.g., *Paramuricea clavata*). These species can form extensive colonies originating structured, biogenic habitats, which provide substrata and refuge for a wide array of species (Orejas and Gili, 2009; Gili *et al*., 2011; Sardá *et al*., 2012; Purroy *et al*., 2014). This is common in biogenic habitats, which are considered important conservation targets (Kaiser *et al*., 2002) threatened by increasing fishing pressure that can negatively impact the complex structure and dynamics of the benthic ecosystems and associated fish species (Thrush *et al*., 1998; Tudela, 2000). Furthermore, this module includes benthic invertebrates currently listed in the IUCN Red List (e.g., the sea fan *Eunicella spp*.), in the BERN and BARCOM (e.g., the sponge *Axinella spp*.), or included in both assessments (e.g., the lobster *Palinurus elephas*). Thus, this module may represent an operational management unit, highlighting the need to regulate the use of trammel nets over biogenic substrata.

In other cases (e.g., Module 0), module membership is explained clearly by fishermen knowledge on the spatial distribution of a given target species (Octopuses) and the choice of a particular fishing gear. This is in agreement with the operational concept of métier, defined as a fishing activity characterized by one catching gear and a group of target species, operating in a given area during a given season (Andersen *et al*., 2012). Species included are often associated to coastal rocky reef areas and to seagrass meadows (e.g., *Posidonia oceanica*). Most are fish species that can be categorized as type 4 (highly mobile or pelagic). Fishing events are characterized by the dominance of octopus traps, occur in shallow waters and are geographically clustered near Palamós port. Octopus traps are commonly deployed in rocky substrates with biotic cover, gravel and pebbles, also a preferential habitat for fish species (mainly sparids) of commercial interest (García-Rubies and Macpherson, 1995). This is an example of a tight correlation between a targeted species and associated by-catch.

On the other hand, the remaining four modules present a heterogeneous and even contribution of the different fishing gears, include both benthic and pelagic species associated with different bottom types and does not present a clear spatial pattern, beyond fishing events being associated with shallow water (depth < 50 m).Module 4, for example, presents species in all 4 type groups and fishing gear associated are gillnets, trammel nets and octopus traps. However, by-catch of the species *Paracentrotus lividus* (BERN: III/BARCOM: III) is associated with this module. Similarly, *Coralium* Directive of the EU and BERN: III/BARCOM: III) is associated with Module 2. Furthermore, module 6 includes the species *Mullus barbatus*, an overexploited species (STECF), and the endangered *Raja undulata* (IUCN) occurs in module 8. Thus, for species of particular interest (threatened or bioengineering species, fisheries interest, etc.), the modularity analysis may help defining a fisheries context for the design of management measures.

Intuitively, one would expect that modules within the by-catch network, if present, should correspond to different fishing tactics or métiers, since both concepts are by definition an operational group based on similarity in gear, target species and operational area, among other factors. However, this seems not to be the case in the present study, since nearly all modules grouped together several fishing gears, despite some exhibiting a high relative frequency of a given fishing gear (e.g., Modules 0 and Module 3). This may be related with the overall lack of correlation between the commercial fraction and by-catch composition observed in the present system, and may be a general feature of multi-species fisheries.

As a rule of thumb, this analysis can be used either to (a) identify units for fisheries management or (b) identify the fisheries ecological context in which a given species is being exploited, thus informing the design of sound management measures (e.g., *Raja undulata* in Module 8). Further, cross-system analysis including several fisheries can be very informative, since differences in the degree (or presence/absence) of modularity may be correlated with differences in the fisheries context. Thus, the allocation of research and/or management resources can be informed based on the expected complexity (or heterogeneity) of a given fishery.

There is ample room for developing the network approach to fisheries management, in order to guide implementation of the ecosystem approach to fisheries management, also recognizing that humans, with their cultural diversity, are an integral component of many ecosystems (CBD, 2004). As shown in this study, one of the most straightforward ways to accomplish this task is to look at raw fisheries data, given that information on the fishing event and associated catch are available. Since decisions on the spatial and temporal allocation of fishing effort, targeted species and fishing gear used involve multiple criteria – including fishermen consideration on ecological, economical, and technical issues – and catch data is informative of the ecological context, these kind of data are a underexploited window to the whole socio-ecological system.

4.3 Hermaphroditic species and small-scale fisheries.

This study shows the diandric protogynous hermaphrodite strategy of common pandora in the studied area; this characteristic has also been observed in other areas for this species (Larrañeta, 1967; Andaloro and Giarritta, 1985; Girardin and Quignard, 1985;

Livadas, 1989; Mytilineou, 1989; Papaconstantinou *et al*., 1988; Pajuelo and Lorenzo, 1998; Klaoudatos *et al*., 2004; Coelho *et al*., 2010; Zarrad *et al*., 2010; Metin *et al*., 2011), reinforcing the idea of the reproductive strategy as stable trait between populations, even when other traits (e.g. size at maturity) may be extremely labile (Lloret *et al*., 2012).

Histology is a particularly crucial tool for reproductive studies of hermaphroditic fish species since details of internal gonad morphology are only visible when histological techniques are used (Sadovy and Shapiro, 1987; Sadovy and Domeier, 2005; Sadovy de Mitcheson and Liu, 2008). The histological assessment demonstrated that the external appearance of gonads is not a reliable indicator of either functional sex or maturity stage outside the spawning period, founding high error rates in sex determination by macroscopic observations. For example, if this study were had considered the macroscopic identification of gonads state, the sex ratio of males to females would have changed from 1: 1.13 to 1 : 1.8 (data not shown).

In other species, as the black sea bass (*Centropristis striata*), histological analysis showed a similar confusion (Wuenschel *et al*., 2012). Results are misleading when there is an under-detection of transitional fish (Wuenschel *et al*., 2012), which at macroscopic level are very difficult to detect. This study shows how histological examination provided the strongest evidence of sex reversal process from ovarian degeneration and spermatogonial proliferation to the development of functional testes in secondary males. This sexual pattern was also supported by the distribution of size class frequencies in which the total length for females was smaller than the secondary males. In addition, the increased abundance of secondary males in the largest size, and to the lower incidence of primary males, confirms the diandric protogyny in this species. This characteristic has also been reported by Valdes *et al*. (2004) in the western Mediterranean Sea.

Through histological examination, were also identified two types of cells likely associated with sex reversal: eosinophils and melano-macrophage centers. The eosinophilic cells seem to be associated with ovary degeneration, as it has been reported for other hermaphroditic fish species, such as the red porgy *Pagrus pagrus*, and the gilthead bream *Sparus aurata* (Kokokiris *et al*., 1999; Liarte *et al*., 2007), and could be used as secondary evidence for the presence of intersexual individuals (Lo Nostro *et al*., 2004).

On the other hand, it has been suggested that one of the key functions of melano-macrophage centres are to act as metabolic dumps for the relocation of debris of effete or damaged cells (Agius, 1980; Agius 1985). As might be expected in a structure with such a function, it has also been observed that these centres increase in size and number as fish grow older and tissues degenerate (Agius, 1981). In the marbled swamp eel *Synbranchus marmoratus*, these structures may act as degradation of atretic and/or non-ovulated follicules, among other functions (Ravaglia and Maggese, 1995).

As observed by the evolution of the gonadosomatic index and histological stages of the gonad development, the main reproductive activity of common pandora in Costa Brava extends from April to July, with spawning mainly concentrated in May and June. The spawning peak is similar to that reported by other authors as Livadas (1989) for the Mediterranean, Pajuelo and Lorenzo (1998) for the Canary Islands, and Coelho *et al*. (2010) for southern Portugal. In addition, Pajuelo and Lorenzo (1998) determined that this species reproduces in the period of the highest water temperature in the Canary Islands. According to Valdes *et al*. (2004), the common pandora spawns when water temperatures are between 22 and 24 °C. The same research states that a rise in temperature causes abnormalities in eggs; therefore, spawning declines in periods with high water temperature.

Primary and secondary males showed interesting differences. Secondary males in spawning capable and actively spawning were found during a larger portion of the year than were females and primary male in these phases. In return, primary males have a more narrower spawning season, being mainly concentrated in June, so as, coinciding with the principal spawning females events. Despite no statistical significant differences were found in the GSI values of the primary and secondary male, primary males showed higher reproductive investment (i.e., higher GSI values) than did secondary males and perhaps suggesting that smaller fish invest energy in sperm production only when absolutely necessary, bearing in mind that for younger individuals it represents a greater effort.

However, these results do not agree with that reported by Valdes *et al*. (2004); these authors suggested that the role played by small primary males during spawning should be null or very limited. In fact, GSI appears to be very low, mainly in secondary males, but also in primary males. GSI has been demonstrated as a proxy for sperm competition, and as an indicator of mating system in fishes (Petersen and Warmer, 1998). Following Erisman *et al*. (2009), comparative analyses of GSI and sexual pattern suggest that sperm competition is significantly higher in gonochoric species than in protogynous species. Values found for common pandora indicates a very low level of sperm competition.

Histological examination of the ovaries revealed that common pandora possess an asynchronous development of follicles, thus, oocytes at different stages of development can be seen altogether in the same specimen along the reproductive period. This gonad development indicates that there are some successive spawning events during the spawning period, so as eggs of a single female should be fertilized by some different males. Moreover, spreading of egg-laying during different events also ensure that some batches progress successfully. On the other hand, testicular tissue of common pandora was of the lobular type, wherein spermatogonia were randomly distributed along the entire length of the lobule in reproductively active fish; this is equivalent to the unrestricted spermatogonial type described by Grier (1980, 1981).

Sex change appears to take place throughout the year and occurs among 30.9–35.7 cm total length. According to Larrañeta (1967), sexual inversion occurs at any time of the year but preferentially in the first half and at 20-23 cm TL. Differences in data may be due to the lack of histological analysis of samples in that study. Coelho *et al*. (2010) reported a similar length at sex change observed in the present study for individuals captured by small-scale fisheries in southern Portugal. The presence of females in the largest size classes implies that sex reversal does not occur in all the population. The sequence shown in figure 9 could be hypothesized for sex differentiation of common pandora. This sequence is comparable with that reported by Larrañeta (1964) in western Mediterranean. According to Vrgoč (2000), it was observed that some specimens were males from the beginning, whereas a number of females do not ever changed their sex, *i.e.*, they remained females even at their greatest body lengths, suggesting that sex change may not only be related to individual determinism but could depend on the environmental and social conditions (Happe and Zohar, 1988). In this regard, Benton and Berlinsky (2006) conducted a lab study manipulating the ratio of females to males in black sea bass (*Centropristis striata*), showing that sex change is, at least in part, triggered by social structure or sex ratios, and similar effects have been found in wild populations of other fish species (*i.e*. Hamilton *et al*., 2007; Shepherd *et al*., 2010).

The Size- Advantage Model (SAM), a widely accepted theory on the significance of sequential hermaphroditism in fishes (e.g. Warner, 1988; Munday, 2002; Erisman *et al*., 2013), proposes that individuals should change sex when the reproductive value of the opposite sex is greater than the current ones (Warner, 1988). According to the results of this study, the reason behind the sex change in common pandora cannot be an increase in the production of gametes, and even less if it is considered that GSI in secondary males is rather low. However, an attempt to maintain a certain proportion of the sexes in the groups seems the more likely hypothesis. In fact, in this study, when sum the number of primary and secondary males, will obtain a nearly 1:1 sex ratio. It really seems that there is a mechanism that stimulates sex change when there is a decrease in the number of males of the population and social interactions seems to be the most likely, considering that, in this species and in their natural environment, large males are often found together with a number of females as discrete groups over extended periods (Buxton *et al*., 1990).

Despite this, another important factor to consider is the selectivity of the fishing gear, the size-selective artisanal fishing affects sex changing fish species because males usually occur at a larger size in those areas where the fishery tends to focus their efforts, thereby skewing sex ratios leading to egg or sperm limitation (Alonzo and Mangel, 2005). In this study, no significant differences were observed in sex ratio, however, several studies have been reported the predominance of females in the population (Vassilopoulo *et al*., 1986; Mytilineou, 1989; Pajuelo and Lorenzo, 1998; Coelho *et al*., 2010; Zarrad *et al*., 2010; Metin *et al*., 2011).

Regarding the implications for the management of the fishery, it could be considered that the small-scale fishery of Palamós performs a sequential exploitation of fisheries resources, taking into account the different gears used by this fishery (Seijo *et al*., 1998). In this technological interdependence, each gear differently affects successive stages of the life cycle of the species involved, affecting their abundance in a dissimilar form (see eg. FAO, 1978). This study showed how the fishing gears analyzed affect differently to the population of common pandora, *i.e.* while bottom long-lines and gillnet may be removing preferentially males, beach seines affects small-sized, so as some young females, but mostly primary males. The removing of little primary males by the beach seines could be a factor that generates the need for change sex to equalize the sex ratio of the population.

In the Costa Brava, a minimum size limit has been implemented for some target species. Although an extremely precautionary manager can well define minimum sizes at first capture based in the upper CI 95% level of bottom long line catches, the mean size at sexual maturity of females (L_{50}) may represent a much less conflictive measure. In the case of the common pandora, however, the current minimum size regulation is of limited benefit because the minimum length which may be legally kept (15 cm total length) is smaller than the mean size at sexual maturity of females (L_{50}) observed in Palamós (19.3 cm). These results suggest that the stock may be currently under-protected due to removal of immature fish, as reported elsewhere (Pajuelo and Lorenzo, 1998; Coelho *et al*., 2010; Metin *et al*., 2011), an mainly by beach seine in this study.

In any case, the minimum legal catch size for common pandora should not only be established considering the L_{50}, recommendations about the minimum length and legal regulations depend on the first reproduction length and the length at which females change to males. In this regard, these findings can be used to determine the appropriate closure season and fish size for sustainable fishing of this species in the region, suggesting that fishing pressure of the species between May and June should be reduced and minimal legal fish size landed set to 21 cm.

In summary, management strategy for *P. erythrinus* should incorporate these facts towards a more effective regulation. Thus, managerial action should take into account a) increasing the minimum legal sizes (currently at 15cm, below the estimation here presented for size at first maturity for females) and b) define temporal and/or spatial closures (i.e. reproductive period and areas), for example during the reproductive season, coincident in Palamós port with the maximum observed landings of the common pandora. Other operative measures, such as a reduction of fishing effort (either by gear modification or regulating effort itself) may be impractical in this context due to the multi-specific nature of the small-scale fisheries at Palamós and the diversity of gears employed. However, the involvement of fishermen in the design of management plans may overcome this issue, leading to satisfactory multi-lateral agreements.

CHPATER 5

CONCLUSIONS

- The implementation of the Ecosystem Approach to Fisheries Management (EAFM) is the current challenge for a proper management of marine ecosystems and resources. An EAFM offers a far greater chance of developing realistic, equitable, and sustainable management plans. This approach pursues sustainability by balancing ecological and human well-being through good governance. Nevertheless, its practical implementation will take time.
- A fully-developed EAFM requires scientific knowledge, based on appropriate data collection, which is largely unavailable at present.
- The usage of an aggregate index, as the Living Planet Index (LPI) was useful to standardize information from SSF of Palamós, a multi-specific fishery (ca. 130 species) that employ a wide array of fishing strategies.
- The results showed a negative trend for LPI_{FP} (Fish Population) and LPI_{FE} (Fishing Effort) across the time series indicating a decreasing socio-ecological sustainability of this fishery.
- According to the theoretical model and despite the slight decrease in LPI_{FE}, the SSF of Palamós was a non-desirable scenario, leading in extreme cases to overexploitation and subsequent fisheries collapse if management actions are not taken.
- At local level, it is recommended that the fishermen guild of Palamós integrates the LPI approach to assess population trends of the species of special interest and define management measures.
- At general level, the LPI approach to fisheries should be adopted by the agencies of national, regional and even international management to identify priority fisheries in order to allocate conservation and/or management resources, targeting either species or ecosystems.

- The above outlined framework only allows focusing on landed species, thereby ignoring the significant component non-targeted species. In this line, a total of ca. 150 by-catch species were observed during the study period, 23.8 % of these listed in the global red list of the International Union for Conservation of Nature.
- Using a network approach, the bipartite graph of fishing events and by-catch species was composed by nine modules or discrete putative management units. The results showed that for species of particular interest (threatened or bioengineering species, fisheries interest, etc.) the modularity analysis should help defining a fisheries context for the design of management measures.
- Of the modules here identified, module 3 is perhaps the most interesting, since is unveiled a significant association between trammel nets and biogenic habitats, which is worth further analysing for the design of management actions.
- The estimation of several parameters related to the life-history traits of *Pagellus erythrinus*, commonly used for fisheries modeling and the design of management strategies was improved.
- These analyzes made also possible the estimation of a more accurate size at sexual maturation in females of *Pagellus erythrinus* (19.3 cm) in Palamós, with sex change occurring year-round over a wide range of sizes generally above this figure.
- In the case of males, fecundity is hypothesized to be not positively correlated with size, and, in this scenario, sex change can maintain a stable sex ratio while actually the population reproductive potential is negatively affected. This biological information should be jointly considered with fisheries data that indicate that different fishing gears affect different population components of this sequential hermaphroditic species. In this sense, a management strategy for

Pagellus erythrinus should incorporate these facts towards a more effective regulation.

- Fishermen perceptions must be used to aid in data interpretation. In addition, the recovery of local ecological knowledge will provide key information to the implementation of a co-management scheme following the principles of EAFM, thus significantly enhancing the likelihood of reaching the CBD Aichi Biodiversity Targets.

CHAPTER 6

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