César Paulo Vieira Gomes

Biology of black scabbardfish (*Aphanopus carbo* Lowe, 1839) and standardization of commercial LPUE data of *Aphanopus spp.* landed in Madeira Archipelago, Portugal

Universidade do Algarve

Faculdade de Ciências e Tecnologia

2016

César Paulo Vieira Gomes

Biology of black scabbardfish (*Aphanopus carbo* Lowe, 1839) and standardization of commercial LPUE data of *Aphanopus spp.* landed in Madeira Archipelago, Portugal

Dissertação para a obtenção do grau de Mestre em

Biologia Marinha

Trabalho efetuado sob orientação de:

Professor Doutor José Pedro de Andrade (UAlg - FCT)

MSc. João Delgado (DRP/SI)

Universidade do Algarve

Faculdade de Ciências e Tecnologia

2016

Título: Biology of black scabbardfish (*Aphanopus carbo* Lowe, 1839) and standardization of commercial LPUE data of *Aphanopus spp.* landed in Madeira Archipelago, Portugal

Declaração de autoria de trabalho

Declaro ser o autor deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referencias incluída.

“We make our world significant by the courage of our questions and the depth of our answers”

Carl Sagan

Acknowledgements

I want to thank everyone who helped me completing this work. A difficult task, helped by many people, many of whom at their own free will, with no obligation to me, nonetheless tireless in seeing this work complete.

It is in this regard that I thank both my supervisors, Professor José Pedro de Andrade, for accepting my request and to guide me through this process, and especially to Dr. João Delgado, Director of the 'Serviços de Investigação da Direção Regional de Pescas', based in Funchal harbour, for embracing positively such initiative, allowing me to perform this study based on data collected by his team.

On a personal note, I thank my family, my parents, sister, grandparents, aunts and cousins, for all the support through the months that took completing this work, for all the emotional ups and downs, something so present in such endeavour, for being there when it mattered. To my girlfriend, Sara, my 'rock' in this entire process, from its earliest moment till the end. Indeed, a life-time achievement for both of us.

I would like to thank several people that, although with no obligation to me, were absolutely tireless in helping me with everything they could. In this regard, first of all, to Adriana Alves, with her most useful comments, suggestions, and great mood, willing to help in whatever manner deemed possible. A special thanks!

To Joana Vasconcelos, for her invaluable suggestions regarding many aspects of the thesis, and for the many advices given and experience shared. Thanks a million!

To Margarida Hermida, for being there every time the ship was about to sink, for her priceless comments, suggestions and advices. My deepest gratitude Margarida, for sharing with me your knowledge on so many aspects. Truly awesome!

To all of my colleagues that shared with me so many moments, especially João Ferreira, a true brother, always present, Miguel Gandra, a proper friend whose invaluable comments and suggestions offered me guidance throughout the whole process, Joana Firmino (the first person I spoke with at the University), the cornerstone of any group, cheerful, responsible, and a good friend, Mariana Santos, with her most interesting and funny comments, Francisca Ribeiro, the adult in the room who we can always rely upon, very supportive and understandable, Andrea Rima, the most righteous person ever, Marisa Magalhães, a friend for the best and the worst times, Anita Alessandrini, Alfonso Díaz, and many others that were present in this endeavour. I thank you from the bottom of my heart!

To my life-time brothers, Paulo Pereira, João Pestana and Salvador Freitas, for their precious support, for kicking me in the butt every time I was down, and for reminding me that true friendship is invaluable.

Lastly but not least, to the people that shared with me the experience while writing the thesis. I have to highlight Fernando Vieira and Jorge Lucas, for the advices given, for the interesting conversations, and for having accompanied me while the process was unfolding.

My sincere gratitude to everyone!

Abstract

The black scabbardfish (*Aphanopus carbo* Lowe, 1839) is a benthopelagic species, member of the *Trichiuridae* family with great commercial and scientific importance in Madeira Archipelago and in the entire NE Atlantic. This work, as part of a bicephalous approach, had two main objectives: perform a biological analysis of *A. carbo*, and to standardize commercial LPUE data of *Aphanopus spp.* landed in Madeira Archipelago (*A. carbo* is not separated from the sympatric species *A. intermedius* for commercial purposes).

In terms of *A. carbo* biology, individuals were collected in Funchal harbour between 2010 and 2015. In this part of the study, the population structure of *A. carbo* was analysed through individual length, weight and sex. The reproductive cycle was inferred through the analysis of GSI, HSI and K_{rel} monthly trends. L_{50s} were estimated by fitting maturity ogives and WLRs and LLRs were calculated through regressions.

Regarding the LPUE standardization, fishery-dependent data was analysed from 2008 to 2015. This part focused on fleet characteristics, the performance of landing trends and effort units. Nominal LPUE was standardized through linear model. The factors affecting the variability of LPUE were obtained and analysis of the overall state of the fishery was made.

In general, *A. carbo* females attain the largest length and weight, the overall sex-ratio differed from 1:1 ratio, with females outnumbering males, spawning is performed in the last quarter of the year, L_{50s} were higher in females than in males, and it exhibits isometric growth in terms of WLRs (except for males) and allometric growth in LLRs.

The standardization of commercial LPUE data revealed an hyperstability state in *Aphanopus spp*. fishery in Madeira EEZ. To compensate lower catches in traditional fishing grounds, fishermen exploit new areas, resulting in stable landing performances. Thus, precautionary management policies are required to sustainably exploit this resource.

Keywords: *Aphanopus carbo*, biology, *Aphanopus spp.*, standardization, LPUE, Madeira Archipelago.

Resumo

O peixe espada-preto (*Aphanopus carbo* Lowe, 1839) é uma espécie bentopelágica pertencente à família *Trichiuridae*. Caracterizado por possuir um corpo alongado, com uma boca terminal grande, olhos igualmente grandes, possuindo uma coloração acobreada-preta, barbatana dorsal muito extensa e dividida em duas partes, e sem barbatanas pélvicas, apresenta uma distribuição ampla por todo o Atlântico NE, sendo particularmente fundamental de um ponto de vista comercial e científico para o Arquipélago da Madeira e para muitas nações costeiras com o Atlântico NE. Este estudo focou-se em duas temáticas diferentes, no que se pode chamar de uma abordagem bicéfala. Assim, foram idealizados dois objetivos principais: fazer um estudo da biologia de *A. carbo*, e realizar uma estandardização de séries comerciais de DPUE de indivíduos do género *Aphanopus spp*. desembarcados nos portos do Arquipélago da Madeira (devido à impraticabilidade de separar *A. carbo* da espécie simpátrica *A. intermedius* nos portos aquando dos desembarques e, portanto, são tratados como um só recurso comercialmente).

Relativamente à biologia de *A. carbo*, os indivíduos foram recolhidos no porto do Funchal entre 2008 e 2015. Nesta parte do trabalho, a estrutura da população de *A. carbo* foi analisada através da recolha de dados de comprimentos, pesos e sexo de cada indivíduo. A análise do ciclo reprodutivo foi feita mensalmente através do IGS, IHS e também do fator de condição relativo, de modo a perceber a variação de cada um na evolução do ciclo reprodutivo. Os L_{50s} foram estimados através das ogivas de maturação e as relações morfométricas de peso-comprimento e comprimento-comprimento foram estimadas através de regressões lineares.

Em relação à estandardização de séries comerciais de DPUE, dados dependentes da pesca foram analisados cobrindo o período de 2008 a 2015. Esta parte do estudo focou-se nas características da frota palangreira madeirense, no desempenho dos desembarques e das unidades de esforço ao longo desse período. A DPUE nominal foi estandardizada através de um modelo linear. Os fatores que afetam a variabilidade dos DPUE foram obtidos, após uma filtragem sucessiva, em que os que violavam os pressupostos do modelo ou que não eram significativos foram abandonados. O resultado foi a obtenção de um modelo que descreve o melhor possível, a variabilidade dos DPUE de *Aphanopus spp*. no Arquipélago da Madeira.

Os resultados obtidos foram analisados cuidadosamente e as conclusões foram retiradas após essa análise. Relativamente ao estudo da biologia de *A. carbo*, foi possível verificar que em águas madeirenses, as fêmeas de peixe espada-preto atingem comprimentos e pesos superiores que os machos. O rácio entre fêmeas e machos foi diferente de 1:1, na medida em que as fêmeas revelaram ser mais abundantes que os machos, não só no total, mas também nas classes de comprimento e peso maiores. Nas classes menores, os machos dominam. A análise do ciclo reprodutivo revelou que a reprodução é feita no último trimestre do ano, entre Setembro e Dezembro. Além disso, chegou-se à conclusão que os machos atingem a maturidade sexual mais cedo do que as fêmeas, confirmado pelos valores de IGS em Agosto, que atingem os valores mais altos em todo o ano. O comprimento à maturidade sexual foi calculado e revelou que as fêmeas atingem a maturidade sexual apresentando um comprimento superior ao dos machos. Por fim, a análise das relações morfométricas de peso-comprimento e comprimento-comprimento revelaram que *A. carbo* cresce isometricamente entre o peso e o comprimento (à exceção dos machos) e que cresce alometricamente entre o comprimento total do corpo e o comprimento da barbatana caudal.

Considerando as características da frota, esta revela possuir uma natureza marcadamente artesanal, em que as embarcações são relativamente pequenas (em 2015 cada embarcação da frota possuía em média um comprimento fora-a-fora de 12.4 m, arqueação bruta de 20 toneladas e 134 Kw de potência de motor), de madeira, a pesca é efetuada na sua essência à mão (colocação do isco nos anzóis e o processo de preparação do palangre é manual). Portanto, evidencia o passado histórico desta atividade no Arquipélago da Madeira.

Relativamente à estandardização dos dados comerciais de DPUE os dados estandardizados foram significativamente inferiores aos dados nominais de DPUE. Tal resultado foi de encontro com as expetativas, na medida em que ao retirar as variáveis que não tinham impacto no cálculo de abundância relativa, a estimativa foi de encontro à realidade e, portanto, os valores são inferiores. Assim, através desta análise chegou-se à conclusão que a pescaria de *Aphanopus spp*. na ZEE da Madeira encontra-se numa situação de hiperestabilidade. Este estado revela que as capturas são superiores à abundância do recurso.

Em consequência, esta situação revela os comportamentos recentes da frota. A frota madeirense tem-se deslocado para outras áreas, fora da ZEE da Madeira de modo a compensar uma menor abundância de *Aphanopus spp.* Esta desloca-se para áreas limítrofes às ZEEs dos Açores e Canárias e mesmo no interior destas de modo a aproveitar as áreas de pesca um tanto ao quanto virgens relativamente a esta pescaria. Assim, o desempenho dos desembarques tem-se mantido em redor das 2000 toneladas nos últimos anos devido a esta forma de compensar a menor abundância deste recurso nas áreas tradicionais de pesca da ZEE da Madeira.

Este estudo abordou de uma forma completa vários aspetos da pescaria de recursos de profundidade do Arquipélago da Madeira. Apesar de haver ainda alguns aspetos que necessitem de estudos subsequentes, o conhecimento relativamente a *A. carbo* e no geral à pescaria de *Aphanopus spp*. permite concluir que, para que uma pesca sustentada deste recurso seja alcançada, este recurso necessita que sejam lançadas novas iniciativas e esforços.

A presença deste recurso em todo o Atlântico NE leva a que medidas de contenção sejam equacionadas, se a preservação deste modo de vida e da espécie é o objetivo final. Uma abordagem transfronteiriça deveria ser o caminho a seguir, em que todas as nações com interesse neste recurso pudessem ter responsabilidades e direitos, congruentes com o direito das nações de explorarem recursos naturais dentro dos territórios por si administrados, sem levarem ao decréscimo populacional ou mesmo à extinção da espécie em causa.

Assim, é nesta perspetiva que este estudo se insere. Para além do conhecimento científico acrescido deste tipo de iniciativas, cujo valor é substanciado por uma maior consciência da população em geral e dos decisores políticos em particular, este estudo visa a que numa perspetiva futura, estejam reunidas as condições para que a exploração sustentada, equitativa e proporcional à dimensão de cada região e sobretudo da espécie, seja alcançada.

Palavras-Chave: *Aphanopus carbo*, biologia, *Aphanopus spp.*, estandardização, DPUE, Arquipélago da Madeira.

General Index

Figures Index

Tables Index

List of Abbreviations

AIC – Akaike Information Criterion

ANOVA – Analysis of Variance

BIC – Bayesian Information Criterion

CECAF – *Fishery Committee for the Eastern Central Atlantic*

CI – Confidence Interval

cm – centimetre

CPUE – Catch-per-unit-effort

DCF – Data Collection Framework

Df – Degrees of Freedom

DPUE – Desembarques-por-unidade-esforço

DREM – Direção Regional de Estatística da Madeira

DRP – Direção Regional de Pescas

DSI - Direção dos Serviços de Investigação

EEZ – Economic Exclusive Zone

EU – European Union

FAO – *Food and Agriculture Organisation*

g – gram

GAM – Generalized Additive Model

GDP – Gross Domestic Product

GLM – Generalized Linear Model

GLMM – Generalized Linear Mixed Model

GSI – Gonadosomatic Index

GT – Gross Tonnage

GW – Gonad Weight

HSI – Hepatosomatic Index

ICES – *International Council for the Exploration of the Sea*

IGS – Índice gonadossomático

IHS – Índice hepatossomático

INIP – Instituto Nacional de Investigação das Pescas

IPMA – Instituto Português do Mar e da Atmosfera

ITIS – *Integrated Taxonomic Information System*

K – Fulton’s Condition Factor

K’ – Allometric Condition Factor

Kg – Kilogram
K_{rel} – Relative Condition Factor
Kw – Kilowatts
L_{50} – Length-at-maturity
LLR – Length-Length Relationship
LM – Linear Model
LOA – Length-Over-All
LPUE – Landing-per-unit-effort
LRT – Likelihood Ratio Test
LW – Liver Weight
m – metre
MO – Mediterranean Outflow
MS_E – Mean Standard Error
MTR – Madeira-Tore Rise
NACO – North Atlantic Central Outflow
NADO – North Atlantic Deep Outflow
NE – North-East
nm – Nautical miles
NW – North-West
PNRDP - Programa Nacional de Recolha de Dados de Pesca
POW – Engine power
r^2 – Coefficient of Determination
RAM – Região Autónoma da Madeira
SE – South-East
SE – Standard Error
SL – Standard Length
STECF – Scientific, Technical and Economic Committee for Fisheries
T_{50} – Age-at-maturity
TL – Total Length
TW – Total Weight
VBA – Analysis ToolPack
WGDEEP - Working Group on the Biology and Assessment of Deep-sea Fisheries Resources
WLR – Weight-Length Relationship
ZEE – Zona Económica Exclusiva

Chapter 1

General Introduction

1. General Introduction

1.1. Study area characterization – *The Archipelago of Madeira*

The archipelago of Madeira is located in the Atlantic Ocean, between 32° 22.3′ N, 16° 16.5′ W and 33° 7.8′ N, 17° 16.65′ W. It is 579 kilometres from the African coast, 861 kilometres from Lisbon, 370 kilometres from Gran Canaria, and 772 kilometres from Santa Maria, the nearest island of the archipelago of the Azores (Martin, 2008; SRA, 2014).

The island of Madeira is the largest island of the archipelago, with 742 km^2, 57 km in length at its longest West – East axis, 22 km in width at the widest point, and a coastal perimeter of some 135 km. The island is characterized by very mountainous terrain and deep valleys, in which roughly 35% of the unsubmerged part attains heights above the 1000 m quota, with the particularity that 90% of the island is above the 500 m quota (Mata *et al.*, 2013). A mountain chain extends along the centre of the island, with several peaks surpassing 1800 m, such as Pico Ruivo (1862 m), Pico das Torres (1853 m) and Pico do Arieiro (1818 m).

Beyond the island of Madeira, the archipelago also includes the island of Porto Santo, with 41 km^2, 11 km in length and 6 km width, lying 28 km NE from Madeira. It is completely different from the main island of Madeira. It is characterized by sandy soils, with very little rainfall throughout the year. It exhibits a somewhat flat profile in the centre of the island, with a more advanced erosive process. Low mountains are present, not exceeding 517 m high (Pico do Facho). A yellow sand beach covers the southern part of the island, with 9 km in length, while the northern part is characterized by rocky cliffs (Geldmacher *et al.*, 2000, 2006; Delgado, 2007; Mata *et al.*, 2013).

It also encompasses several islands and islets with no permanent resident population, such as the Desertas Islands, stretched in NNE-SSW direction – Deserta Grande (10 km^2), the largest island and sole safe haven for the endemic population of wolf spider *Hogna ingens* (Blackwall, 1857), one of the largest and rarest wolf spider species (Crespo *et al.*, 2014), Bugio (3.3 km^2) and Ilhéu Chão (0.43 km^2) – located SE off Madeira, at a distance of 2 km. It is also an important site for the critically endangered Mediterranean monk seal, *Monachus monachus* (Hermann, 1779), in which a small colony of about 30-40 individuals are present (Pires *et al.*, 2008; Hale, 2009; Pires, 2011).

Administratively, it also includes the Selvagens Islands. It is composed of Selvagem Grande (2.46 km^2), characterized by steep cliffs along the coast, reaching a height of 163 m (Pico da Atalaia), Selvagem Pequena (0.16 km^2) characterized by gentle cliffs and sandy/rocky beaches, with high tidal amplitude, and Ilhéu de Fora (0.071 km^2). The islands are located relatively near the Canary Islands, at a distance of about 165 km, and about 250 km from Madeira (Mata *et al.*, 2013).

1.2. Maritime space

The width of the territorial waters (belt of coastal waters extending up to a limit of 12 nm) and the establishment of the Economic Exclusive Zone (EEZ) (zone of the sea stretching from the baseline up to 200 nm from its coast) of Portugal were consecrated by the United Nations Convention on the Law of the Sea in 1982 and settled by the Portuguese Law-Decree nº 119/78 (Delgado, 2007; SRA, 2014).

The sub-area 2 of the Portuguese EEZ, called the Madeiran EEZ encompasses an area of approximately 446108 Km^2 (*Figure 1.1*). Besides the islands and islets referenced above, it also includes several fishing banks (Seine, Lion, Unicorn, Dragon, Susanna, Ampère and Josephine, these last two extending beyond the Madeira EEZ) mainly distributed along a North-Northeast direction in which the nearest (Seine) is located roughly 300 km from the island of Madeira (Delgado, 2007; SRA, 2014; STECF, 2014).

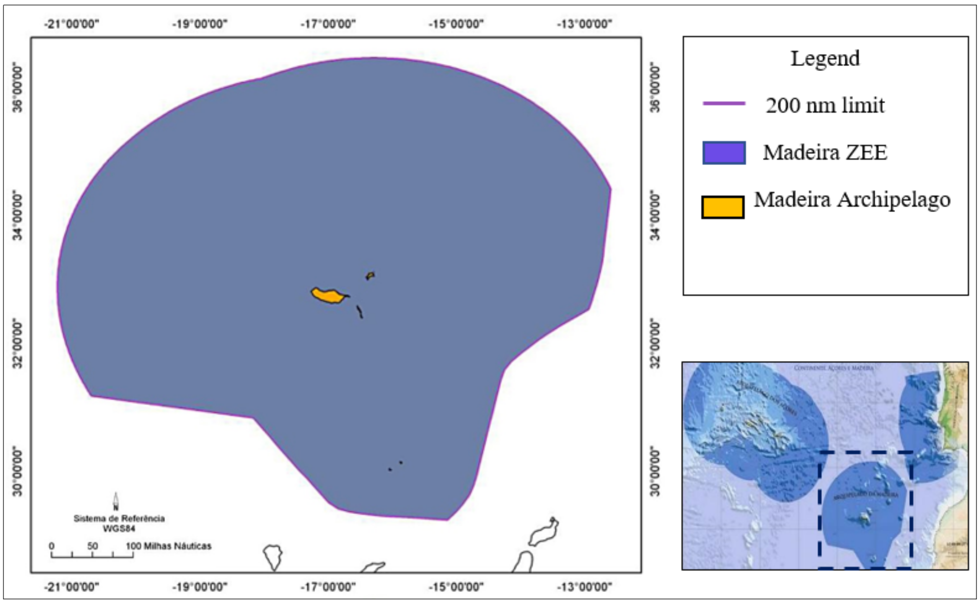


Figure 1.1. Exclusive Economic Zone of Madeira (from SRA, 2014).

1.3. Geomorphology and seabed topography

The archipelago is located on 140 Myr old oceanic crust, within the African plate, (Pitman & Talwani, 1972) and rises from more than 4000 m water depths up to 1862 m above sea level (Pico Ruivo mountain). It is a part of the Madeira-Tore Rise (MTR) complex, stretching roughly 1000 kms (*Figure 1.2*) (Geldmacher *et al.*, 2000, 2006; Silveira *et al.*, 2010). It locates on a NE trending submarine ridge in the Central-Eastern Atlantic, bounded by abyssal plains to the west and south and by a number of large isolated seamounts on its eastern side (Gorringe Bank, Hirondel, Ampère/Coral Patch, Unicorn, Seine) and the Madeira Islands to the southeast (Geldmacher *et al.*, 2000, 2006; Silveira *et al.*, 2010; Mata *et al.*, 2013).

The islands constituting the archipelago of Madeira are consensually considered a *hotspot* product, whose origin is attributable to an oceanic magmatic source from which a long-term mantle plume originated a series of submarine eruptions (Geldmacher *et al.*, 2000, 2006; Silveira *et al.*, 2010; Mata *et al.*, 2013). The emergence of the volcanic complex of Madeira-Desertas (united by isobath of 200 m), from a series of submarine eruptions, dates back 5.2 Myr ago in the Superior Miocene, posterior to the formation of the island of Porto Santo, dating back 13.5 to 18 Myr old, in the Inferior-Middle Miocene (Ferreira, 1985; Ferreira *et al.*, 1988; Ferreira & Neiva, 1996; Geldmacher *et al.*, 2000, 2006). As for the origin of the Selvagens Islands, based on their geographical-geological positon and its chemical affinities, it can be linked to the formation of the Canary Islands, owing its origin to the Canary *hotspot*, dating back roughly 27 Myrs (Geldmacher *et al.*, 2000, 2006). The Desertas Islands, based on ^{40}Ar/^{39}Ar age determination, were estimated to date back 5.07 to 1.93 Myrs (Zbyszewski *et al.*, 1973; Schwarz *et al.*, 2005; Geldmacher *et al.*, 2000; Ech-chakrouni, 2004). The process from which the islands were formed was characterized by several stages, with stages of eruptions punctuated by erosion and sedimentation processes in between. The last recorded eruption in Madeira dates back 6000-7000 years (Geldmacher *et al.*, 2000, 2006; Silveira *et al.*, 2010; Mata *et al.*, 2013).

One of the marking aspects of the islands is the sheer morphology of its rock masses. These are true mountains, rising above the sea floor at 4000 metres depth, isolated from the African continental shelf and separated by huge depths of thousands of metres. The insular shelves are very narrow, characterizing the bathymetry of these islands by steep declines (Geldmacher *et al.*, 2000, 2006; Delgado, 2007; Silveira *et al.*, 2010; SRA, 2014; Mata *et al.*, 2013).

These series of features coupled with the isolation from the nearest mainland masses of Africa and Europe grant these islands a distinctly oceanic nature, being one of the determining factors of its marine faunas and the availability of existing fishery resources, situation common to other islands such as the Azores and the Canary Islands (Geldmacher *et al.*, 2000, 2006; Delgado, 2007; Silveira *et al.*, 2010; SRA, 2014; Mata *et al.*, 2013).

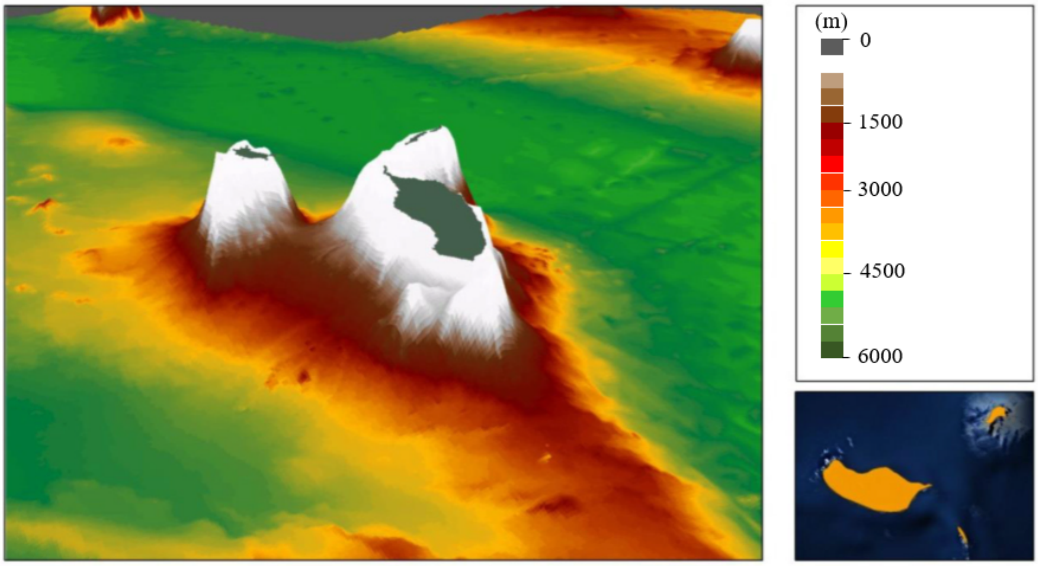


Figure 1.2. Bathymetric map of Madeira Archipelago (from SRA, 2014).

1.4. Climate

The climate of the islands is mainly influenced by the tropical anticyclone of the Azores (Delgado, 2007; Silveira *et al.*, 2010). The archipelago is located in a subtropical region, exhibiting mild temperatures all year round. Capelo *et al.* (2007) classified the climate of Madeira as mediterranean and temperate. On the South coast, below the 1000 m, and on the lowlands of the North coast the climate is characterized by a long season of very little precipitation during the summer months. Above the 1000 m on the South coast and on most of the North coast, the climate is temperate, with precipitation well distributed over the year (a consequence of the persistence of fogs resulting in indirect precipitation), without a dry season and with permanent availability of water in the soil. Thus, a rather remarkable thermal variation occurs between the mountainous terrain and the deep valleys, with very high temperatures in the lowlands and low temperatures high in the mountains, low enough for snow to be abundant in the coldest months (Borges *et al.*, 2008).

Therefore, a clear difference can be observed from the southern to the northern coast. The existence of a central massif, with sharp reliefs, causes a marked variability in the distribution of precipitation values, relative humidity and temperature, whether in height or in the slopes with different exposure to prevailing winds, contributing to the existence of microclimates (Delgado, 2007; Silveira *et al.*, 2010).

The lowest average elevation of Porto Santo can explain the fact that, despite its relative proximity to Madeira, a very different climate regime prevails on the island. Porto Santo has very little rainfall throughout the year (<400 mm), prone conditions for the development of 'bad-lands' in which the waterways are desiccated most of the year. Thus, the climate in the island is more homogenous than in Madeira, exhibiting similar morphological characteristics of semi-arid regions, with the exception of small cliffs areas facing north (Mata *et al.*, 2013).

The scenario in the rest of the islands that compose the archipelago are very much similar. The Desertas and Selvagens Islands are mostly semi-arid, with low precipitation rates (Mata *et al.*, 2013).

1.5. Oceanographic characteristics

In terms of its hydrology, this area is influenced by three water masses: the North Atlantic Deep Outflow (NADO), the North Atlantic Central Outflow (NACO) and the Mediterranean Outflow (MO). The NADO predominates below 1400 m (although it is mostly present under 2000 m) while the NACO is mainly present down to 500-600 m depth and. Both water masses have a highly significant correlation between salinity and temperature (Pissara *et al.*, 1983).

The influence of the MO is mainly present at depths lower than 600 m and down to 2000 m and does not exhibit a correlation between temperature and salinity (Pissara *et al.*, 1983). It is characterised by relatively stable though high salinities and temperatures in relation to the depth at which it is found (Pissara *et al.*, 1983). Passing the Gibraltar Strait, it divides into a northern component that extends into the deep water off Portugal and can be detected in the Porcupine Seabight (Rice *et al.*, 1991) and Rockall Trough (Ellett *et al.*, 1986) and into a southern component that reaches Madeira waters. It has several cores although the two most important lie at 800 and 1200 m (upper and lower core respectively) (Ambar & Howe, 1979). This interval corresponds to the depth at which the black scabbardfish is mainly caught, so it is commonly associated with MO. In fact, experimental research cruises carried out between 1979 and 1987 by the ‘Instituto Português do Mar e da Atmosfera’ (IPMA) showed that the highest abundance was achieved northeast of Madeira Archipelago, in the Seine, Lion, Gorringe, Ampère and Unicorn seamounts (Leite, 1988), an area where the MO influence was higher (≥ 68% in the Ampère and Gorringe seamounts) than in the waters around Madeira Island, where the MO influence is around 40% (Pissara *et al.*, 1983) and the fish abundance is thus lower.

1.6. Biogeographic characteristics

The archipelago is part of the Macaronesia region, sharing this common trace with other archipelagos from the NE Atlantic, including the Azores, Canary Islands, Cape Verde and also an African enclave, between Moroccan Atlantic coast and Western-Sahara coast (Lloris *et al.*, 1991; Delgado, 2007). Initially designated by English geologist and botanist Philip Baker Webb, is considered as such primarily due to its flora and particularities (Delgado, 2007; Marques, 2013).

The origin of the existing flora of Madeira and in general the islands of Macaronesia has been debated by various authors (*e.g.* Capelo *et al.*, 2007; Marques, 2013). This is seen as a remanence of an ecological corridor, which occupied southern Europe and North Africa during the Paleogene (65 – 23 Myrs), and this particular type of flora would be then designated as Paleotropical Geoflora (Mai, 1989; Barrón *et al.*, 2010).

Upon the disappearance in the mainland of this type of forest, during the inferior Pliocene due to severe climatic changes (significant changes in precipitation patterns, glaciation events and also linked to desertification events that originated the Sahara desert), originating a new floristic scenario in the Quaternary, many genera are only found today in the Atlantic archipelagos, restrict to them and designated as paleoendemisms, owing this designation to the similarity of the forests from those eras to those predominant in the archipelagos (Capelo *et al.*, 2007; Barrón *et al.*, 2010; Marques, 2013).

The Macaronesian region, due to its geographical location, singularity in terms of ecological conditions and isolation of the islands themselves (one of the single greatest tool for speciation and endemism) from other land masses, confer these islands with extraordinary diversity of plant and animal species, some of them unique in the world. Thus, it is considered a relic from a long past age, an unmatched place for species biodiversity due to its high percentage of endemism (Capelo *et al.*, 2007; Barrón *et al.*, 2010; Marques, 2013). The

Madeira Islands are intrinsically linked to this notion, in which, besides the island of Fuerteventura in the Canary Islands, it is the region where higher endemism rates are present (Capelo *et al.*, 2007).

Although floristically very important and significant, in terms of ichthyology, the term Macaronesia is not used considering this aspect. Several studies have been conducted throughout the years, mainly concerning the faunal diversity in the archipelagos. In general, several authors refer to Madeira islands as diverse in terms of marine fauna, mainly in the neritic area, although characterized by small populations, a feature common with areas in which the waters are marked by great depths, with very narrow continental shelfs and predominantly oligotrophic, hence not supporting a great numbers of species as the tropical waters can (Delgado, 2007).

1.7. Fisheries in Madeira

1.7.1. Overview

The fishing activity in Madeira has always been important, since the early settlers arrived in the 15th century. As such, the historical socio-economic relation which the population has with this activity is very much an intrinsic part of the historical roots of the islands. Several towns and villages are named after fishing resources, thus reflecting such importance (Gonçalves & Nunes, 1990).

Though quite common an insular region having such roots, nowadays the fishing sector has seen better days, resulting from a product of a mixture of economic development, globalization and world trade. Nowadays, it has a small influence in the archipelagos' economy revealed by the decaying influence of the sector and other primary activity sectors, contrasting to the positive evolution of the tertiary sector (services). Consequently, the fishing sector accounts for only 0.7% of the regions' gross domestic product (GDP) and employs a mere 0.9% of the islands' working force, though accounting for 36% of the total exports from Madeira (Martin, 2008). The region possesses several ports where fish can be landed, being the ports of Funchal and Caniçal the largest, representing most of the disembarked fish and commodities in Madeira respectively.

The fishing sector in the archipelago in encompassed by an enormous oceanic region, strongly influenced by several natural variables which determine the environmental characteristics of marine ecosystems (SRA, 2014). Within these, it should be highlighted the oligotrophic nature of Madeiran waters, although sporadic periods linked to an oceanographic phenomena known as the 'island effect' in which deeper, colder and nourished waters rise up to upper layers in the water column promoting punctual surges in primary production rates (Caldeira *et al.*, 2002; SRA, 2014), specially near the coasts of Madeira, Porto Santo, and Desertas Islands (Caldeira *et al.*, 2002).

The volcanic origin of the archipelagos' islands, which are steep mountains emerging from the abyssal plain of Madeira, determined the geomorphological features of the seabed, where the narrowness of the insular platform, to the depth of 200 meters, stands as clearly limiting factor for fishing activity reducing the area of available habitat for coastal demersal species. On the other hand, the slope, marked by steep inclines and submarine canyons, led to the use of certain fishing gear, particularly those that do not necessarily come into direct contact with the seafloor (Caldeira *et al.*, 2002; SRA, 2014).

This set of features have led the fishing activity towards the exploitation of oceanic resources, namely large pelagic migratory species (tunids) and also deep-water fishes (black and intermediate scabbardfish), a situation that was accentuated from the 80's onwards when the autonomy of the fleet, carrying capacity and conditions for captured fish conservation improved significantly (SRA, 2014), and gradually transitioned from a family activity developed mainly by small boats, often non-motorized, along the coast for an activity that has become predominantly more specialized, adventuring further away from the coast, reaching fishing grounds off the Canaries and south of the Azores (SRA, 2014).

1.7.2. Halieutic resources

The fishing sector in Madeira is subdivided in several types, varying according to the type of fishing resource exploited, fishing vessels and fishing methods. Hence, four categories can be clearly distinguished, namely the tuna fishing, the black scabbard fishing, the small pelagic fishing (locally known as "ruama") and other types of fisheries (Delgado, 2007; SRA, 2014).

The fishery activity in Madeira is very concentrated. Only two fisheries, black scabbardfish and tuna (*Katsuwonus pelamis* and *Thunnus obesus*), represent around 80%-85% of catches. Tuna species is particularly important as it represents around 50% of total catches and black and intermediate scabbard (*Aphanopus carbo* and *Aphanopus intermedius* respectively) fishing around 30%-40 of total catches (Martin, 2008; DREM, 2015a; SRA, 2014). Also, regarding the economic output of this activity, black scabbardfish and tuna represent the majority of revenue. Although black scabbardfish is caught in lesser numbers than tuna, due to its market value, both fish resources do not vary significantly when considering their selling price and subsequent returns (SRA, 2014; DREM, 2015b).

Tuna is a fundamental fishing resource for the archipelago, being a deeply-rooted tradition, with many years of activity. The main targets are skipjack tuna (*Katsuwonus pelamis*) and bigeye tuna (*Thunnus obesus*), but also other species are present such as the albacore tuna (*Thunnus alalunga*), the yellowfin tuna (*Thunnus albacares*) and Atlantic bluefin tuna (*Thunnus Thynnus*). Capture is made through the pole and line fishing method, using live bait, usually mackerel. It is performed by throwing the bait onto the tuna shoal, from which the vessel is positioned upon, pulling them out from the water with a pole and line (hence the name), catching one individual at a time (Shon *et al.*, 2015). This fishery comprises the biggest boats in the fleet and is influenced by the environmental conditions that determine the migratory pathways in which the tunas roam (Fonteneau, 1998; Caldeira & Lekou, 2000; Delgado, 2007).

The black scabbardfish fishery dates back centuries ago in the archipelago, being emblematic to the region. It is exploited by the artisanal longline fishery, relying on drifting mid-water longlines, placed horizontally hundreds of metres deep to maximize capture. It is regarded as highly selective since it targets specifically adult black scabbardfish, diminishing the possibility of bycatch (Delgado, 2007; Bordalo-Machado *et al.*, 2009; Gordo, 2009; Gordo *et al.*, 2009; Farias *et al.*, 2013; Santos *et al.*, 2013a). Other fleets target this resource, in which the French fleet is more expressive (though recently accompanied by Spanish, Faroese and Icelandic fleets), whom capture method is through mixed trawling, *i.e.*, bottom and mid-water trawling (Bordalo-Machado & Figueiredo, 2009; Bordalo-Machado *et al.*, 2009; Santos, 2013).

The other also relevant fishing resources exploited in the archipelago are the ones targeting blue jack mackerel (*Trachurus picturatus*) and Atlantic chub mackerel (*Scomber colias*). Its importance relies on the tradition that the local population has with these resources, being deeply rooted in the local gastronomy and socio-cultural tradition. Also, these resources are important as bait for other types of fishery, namely tuna and black scabbardfish (Delgado, 2007; SRA, 2014).

Other fisheries have also an influence on the structure of the archipelagos' fishing industry. Although relatively small comparing to previously referenced species, the demersal fishes have still influence in the industry. These species are greatly valued, being the target of a multi-specific fishery, by small vessels, in an artisanal process (Delgado, 2007; SRA, 2014).

1.8. Deepwater fisheries

The appreciation of how abundant marine life was in the past has become increasingly difficult since people keep reducing expectations as we forget former conditions (Pauly, 1995). This concept, described as shifting baseline syndrome, is now clearly visible in fisheries (Pauly, 1995). After reaching Labrador in 1508, Sebastian Cabot described Atlantic cod (*Gadus morhua*) abundant enough to obstruct his ships' movement. Two centuries later, Pierre de Charlevoix associated quantities of Grand Banks cod to grains of sand, calling cod fisheries ''mines'' more valuable than the mines of Peru and Mexico (Roberts, 2007). In 1992, after centuries of exploration, a moratorium was decreed by the Canadian government suspending the northern cod fishery in Newfoundland. The population had crashed far below healthy numbers. Twenty years after the suspension, the population had not yet recovered (Finley, 2009; Frank *et al.*, 2011).

The situation in which the world fisheries is positioned can be related to the 'tragedy of the commons' from Hardin (1968), after an essay from Victorian economist William Foster Lloyd in 1833 for explaining unregulated grazing of common land in Great Britain. Although quite regulated nowadays, this wasn't and still isn't always the case since many resources have been pushed close to the brink of extinction (Pauly, 1995).

From the example given previously, the activity of fish exploitation, since centuries ago until around the mid 80's concentrated its efforts in exploring marine resources in continental shelves, being responsible for more than 95% of the global catches (Merret & Haedrich, 1997; Haedrich *et al.*, 2001). The situation is now slightly different. Although unregulated fishing still occurs, new fishing grounds are now being exploited in order to keep up with the world demand.

As traditional fisheries in continental shelves started to decline, a change from exploiting large predators in numerous areas around the globe has triggered fisheries to target species of lower trophic levels in what is known as 'fishing down marine food webs' (Pauly *et al.*, 1998). Not only new fish resources started to be exploited but also new fishing areas as well, many of whom only recently explored. As so, distant water fleets started to exploit resources in areas of open ocean and from less accessible deep water resources (Morato *et al.*, 2006; Norse *et al.*, 2012).

Improving markets, overfishing of continental shelves, and also unregulated deepwater fisheries, were the reasons behind this shifting scenario (Santos *et al.*, 2013). Thus, deep water fisheries quickly expanded, in contrast to the continental shelf fisheries (Santos, 2013; Morato *et al.*, 2006; Norse *et al.*, 2012). During decades, programmes to collect biological and fisheries data were absent from deepwater fisheries. Though increasing in the last few decades, our understanding still lacks on the population dynamics of many deepwater species and the impacts these activities have on them (Morato *et al.*, 2006).

Deep-water fish resources are generally considered to have high longevity, slow growth rates, late sexual maturation, and low fecundity. Such that deepwater stocks can be rapidly depleted and recovery can be very slow (Morato *et al.*, 2006). Thus, they have been considered more vulnerable to exploitation than most species exploited on the continental shelf, upper continental slope or in open ocean pelagic ecosystems (Merrett & Haedrich 1997). Therefore, considerable biological and ecological knowledge is required in order to determine which species are sustainable to commercial fisheries and how they can be managed properly (Merrett & Haedrich, 1997).

It is on this previously mentioned scenario that the black scabbardfish is inserted. Black scabbardfish is a charismatic inhabitant of the deeps and one of the main deepwater commercial species in Europe, where it is captured by multi-species trawlers in the North of Europe and by a small scale longliners in Portugal, not only in coastal areas of the mainland but also in the Azores and Madeira EEZ (Bordalo-Machado & Figueiredo, 2009; Bordalo-Machado *et al.*, 2009; Gordo, 2009; Gordo *et al.*, 2009; Farias *et al.*, 2013). It represents an important fish resource for Portuguese fisheries, but mainly for Madeira Archipelago, since it is a long exploited resource. Several studies have been published regarding this species, concerning the species' population dynamics, fishery status and management efforts have been applied throughout the years. It is on this perspective that the next chapter will be developed, focusing on this deepwater resource.

1.9. *Aphanopus carbo* Lowe, 1839

1.9.1. Species description

The black scabbardfish, *Aphanopus carbo* Lowe, 1839, is a benthopelagic species belonging to the family *Trichiuridae* (Nakamura & Parin, 1993). It is taxonomically classified, according to the *Integrated Taxonomic Information System (ITIS)*, as follows:

Kingdom Animalia
    Phylum Chordata
        Superclass Osteichthyes
            Class Actinopterygii
                Order Perciformes
                    Family Trichiuridae
                        Genus *Aphanopus* Lowe, 1839
                            Species *Aphanopus carbo* Lowe, 1839

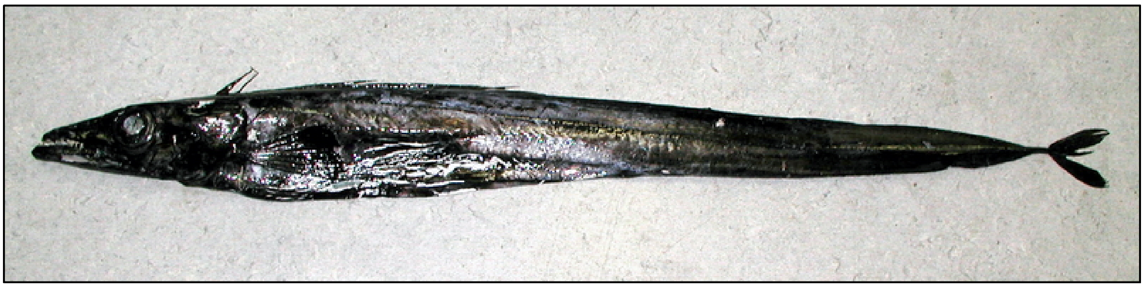


Figure 1.3. Black scabbardfish (*Aphanopus carbo* Lowe, 1839) (from the Municipality of Funchal website. Url: http://www.cm-funchal.pt/ciencia/index.php?option=com_content&view= article&id =243:espada-preto&catid=109:especie-do-mes&Itemid=338)

It is characterized by an extremely elongated and compressed body, with a small V-shaped or forked caudal fin, adapted for fast swimming (*Figure 1.3*). Possesses a large terminal mouth with large and strong fang-like teeth in the anterior part of the upper jaw for efficient predation, one nostril on each side of the snout and pelvic fins absent or reduced to 1 scale-like spine and 0-2 rudimentary soft rays (Nakamura & Parin, 1993; Gordo, 2009; Farias *et al.*, 2013). Exhibits no scales whatsoever, has large eyes to facilitate sight in low light (Farias *et al.*, 2013; ICES, 2014), and displays a coppery-black colouration with an iridescent tint (Nakamura & Parin, 1993; Farias *et al.*, 2013).

1.9.2. Distribution

This species is widely distributed throughout the North Atlantic between 30º N and 70º N (Reis *et al.*, 2001; Farias *et al.*, 2014; ICES, 2014), with records from Iceland (Magnússon & Magnússon, 1995) to the Canary Islands and Western Sahara coast (Uiblein *et al.*, 1996), including the islands of Madeira, Azores and numerous submarine banks and seamounts (Nakamura & Parin, 1993; Parin, 1995; Morales-Nin & Sena-Carvalho, 1996; Pajuelo *et al.*, 2008; Machete *et al.*, 2011). It has also been caught in the western part of the Atlantic, in Greenland, Canada and the USA (*Figure 1.4*) (Templeman & Squires, 1963; Fitch & Gotshall, 1972; Parin & Becker, 1972; Peden, 1974; Clarke & Wagner, 1976; Gorbunova, 1977; Howe *et al.*, 1980; Nakamura, 1984; Borets, 1986; Lauth, 1997; Farias *et al.*, 2013; ICES, 2014).

As a benthopelagic species, *A. carbo* has been caught between depths of 200 m (Nakamura & Parin, 1993) and 2300 m (Pajuelo *et al.*, 2008), although is most abundant at between 400 and 1400 m off the west of the British Isles (Ehrich, 1983; Allain *et al.*, 2003), 800 and 1800 m in mainland Portugal (Martins *et al.*, 1987), and 800 and 1300 m in Madeira (Morales-Nin & Sena-Carvalho, 1996; Delgado *et al.*, 2013).

It is usually caught at shallower depths on the continental shelf and at deeper depths on the island slopes (Morales-Nin & Sena-Carvalho, 1996; Nakamura & Parin, 1993; Delgado *et al.*, 2013). Average length and maximum length of black scabbardfish caught west of the British Isles are smaller than those caught off mainland Portugal, which in turn are smaller than those caught off Madeira (ICES, 2014). Mature or spawning individuals have never been recorded west of the British Isles or mainland Portugal and the only known spawning locations are around Madeira, the Canary Islands and the Northwest coast of Africa (Figueiredo *et al.*, 2003; Pajuelo *et al.*, 2008; Santos *et al.*, 2013a; ICES, 2014). Evidence from otolith microchemistry and stable isotope analysis are consistent with the fish caught west of the British Isles and Portugal having been spawned at latitudes similar to Madeira (Santos *et al.*, 2013b; ICES, 2014).

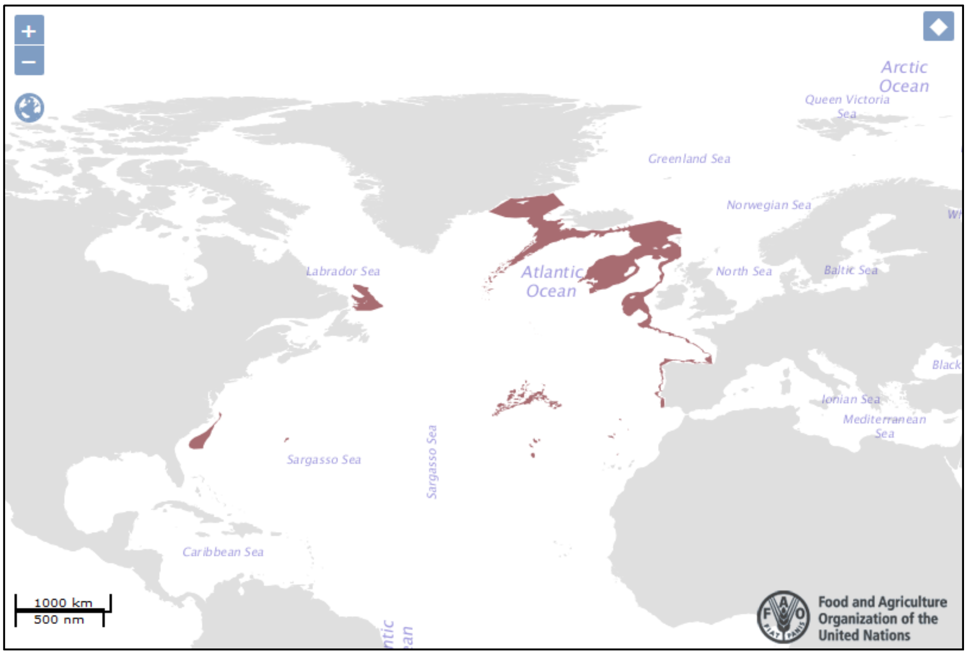


Figure 1.4. Distribution of black scabbardfish (*Aphanopus carbo* Lowe, 1839) (from the Aquatic Species Distribution Map Viewer of FAO website. Url: http://www.fao.org/figis/geoserver/factsheets/species.html).

1.9.3. Age, growth and length structure

Many studies have been conducted and several conclusions have been withdrawn regarding length structures and age and growth features. The studies carried out showed that the individual size of black scabbardfish ranged was smaller in northern latitudes, increasing moving south, attaining its largest length in Madeira, Canary Islands and NW coast of Africa (Morales-Nin & Sena-Carvalho, 1996; Anon, 2000; Reis *et al.*, 2001; Figueiredo *et al.*, 2003; Pajuelo *et al.*, 2008; Perera, 2008; Farias *et al.*, 2013; Delgado *et al.*, 2013; Santos *et al.*, 2013a). This variation was mentioned by Figueiredo *et al.* (2003), who showed different length ranges off NW Scotland (61.2 - 117.5 cm TL), Sesimbra (66.7 - 136.5 cm TL) and Madeira (71.2 - 151 cm TL) (Bordalo-Machado & Figueiredo, 2009). Also, length changes according to sex, since females attain greater lengths than males, confirmed by many studies in the field (*e.g.* Figueiredo *et al.*, 2003; Bordalo-Machado *et al.*, 2009; Santos *et al.*, 2013a; Delgado *et al.*, 2013).

Several authors have embarked in calculating length at first maturity (L_{50}) for black scabbardfish. Magnússon *et al.* (2000) estimated L_{50} to be 92-97 for females cm 84-88 cm for males off Iceland. Anon (1999b) estimated L_{50} to be 85 cm for females and 91 cm for males in Hatton Bank. Figueiredo *et al.* (2003) estimated L_{50} to be 103 cm for females off Madeira. More recently, Santos *et al.* (2013a) estimated L_{50} for Madeiran specimens to be 111 cm for females and 101 cm for males. Delgado *et al.* (2013) estimated L_{50} to be 117.5 cm for females and 97.6 cm for males. Pajuelo *et al.* (2008) estimated L_{50} to be 114 cm for females and 109.5 cm for males off Canary Islands. Hence, a pattern is clearly visible, in which L_{50} increases as latitude decreases, attaining greater values in the southern areas, off Madeira, Canaries and NW African coast.

Age readings has varied throughout the years. At first, the maximum age was estimated to be 8 years for fish from Madeira (Morales-Nin & Sena-Carvalho, 1996) and 32 years from the Rockall Trough (Kelly *et al.*, 1998). Posteriorly, it was determined to be 12 years for Madeira and the Canary Islands. In recent endeavours, age was estimated to be 12 years in the mainland Portugal (Vieira *et al.*, 2009) and 14 years in Madeira (Delgado *et al.*, 2013). The difference associated to these studies not only lies on the different regions where individuals were sampled but also on the techniques of otolith preparation and reading, to the lack of differentiation between *A. carbo* and *A. intermedius* in some studies, and hence should be approached carefully.

The growth parameters estimated by several authors (*e.g.* Morales-Nin & Sena-Carvalho, 1996; Pajuelo *et al.*, 2008; Vieira *et al.*, 2009; Delgado *et al.*, 2013) showed that the black scabbardfish exhibits relatively rapid growth rates when comparing to other deepwater species.

1.9.4. Reproduction

The black scabbardfish is an iteroparous species, *i.e.*, spawn occurs multiple times throughout its life, and also a total spawner, *i.e.*, spawn occurs in one single event (Pajuelo *et al.*, 2008; Santos *et al.*, 2013a). Spawning takes place in the southern areas of the distribution, off Madeira, Canary Islands and possibly in NW coast of Africa, in the last quarter of the year, from September to December (Bordalo-Machado *et al.*, 2001; Figueiredo *et al.*, 2003; Pajuelo *et al.*, 2008; Perera, 2008; Vieira *et al.*, 2009; Delgado *et al.*, 2013; Santos *et al.*, 2013a).

Several works have been developed in order to better understand the reproductive cycle of this species. Pajuelo *et al.* (2008) by studying biological parameters of *A. carbo* off Canary Islands got to the conclusion in which that region is also a spawning ground for this species, since all specimens in all maturity stages were found, similar to Madeira, something that previously was not known.

The project APHACARBO, whose goal was to perform a comprehensive study on the reproductive strategies of black scabbardfish in the southern Northeast Atlantic, in Portuguese mainland coast, and in Madeira (Neves *et al.*, 2009), confirmed the non-existence of spawners in the Portuguese mainland coast.

Another study regarding the reproductive cycle was conducted by Santos *et al.* (2013a). Individuals were sample from two geographical regions, west of the British Isles and from Madeira. Decisive conclusions were withdrawn. Individuals from the northern region were immature throughout the year, but the ones from the southern area were mature, corroborated the GSI values.

The study of reproduction arose several questions regarding the life cycle and the distribution of the species. Why does *A. carbo* not mature and spawn somewhere else than Madeira and the Canaries? Can *A. carbo* spawn on consecutive years? Although still debated by many specialists in the field, a migration hypothesis arose and is generally accepted throughout fisheries experts.

1.9.5. Migration

The life cycle of black scabbardfish still raises some questions, but the most common hypothesis is that one single stock undertakes a large scale clockwise migration around the NE Atlantic (*Figure 1.5*) (Figueiredo *et al.*, 2003; Delgado *et al.*, 2013; Farias *et al.*, 2013, 2014; Santos *et al.*, 2013a).

The reason why such migration takes place is still cause for debate but many agree that it is related to feeding and reproduction. A factor that may prompt *A. carbo* to migrate is the migration pattern of blue whiting (*Micromesistius poutassou*), the preferred prey item in the northern area. Blue whiting undertakes extensive distance migrations from the breeding grounds to the west of the British Isles to the feeding grounds off Norway by the end of April (Bailey, 1982; Was *et al.*, 2008). This in turn originates a shift from a diet predominated by blue whiting in the first quarter of the year, to a less nutritional diet, composed of cephalopods and crustaceans in the second quarter onwards (Santos *et al.*, 2013b). This alteration may result in a decrease in the black scabbardfish condition to advance with maturation and trigger the migration (Santos *et al.*, 2013a; Farias *et al.*, 2014). Considering a stock, *i.e.*, a group of fishes with similar life history characteristics large enough to be self-reproducing (Hilborn & Walters, 1992), it makes sense that *A. carbo* develops in one single stock throughout the North Atlantic, since the study of oocyte dynamics and reproductive strategies (Santos *et al.*, 2013a), otolith shape (Farias *et al.*, 2013), and microchemical analysis of the larval potion otoliths (Longmore *et al.*, 2011) are highly in favour of this hypothesis.

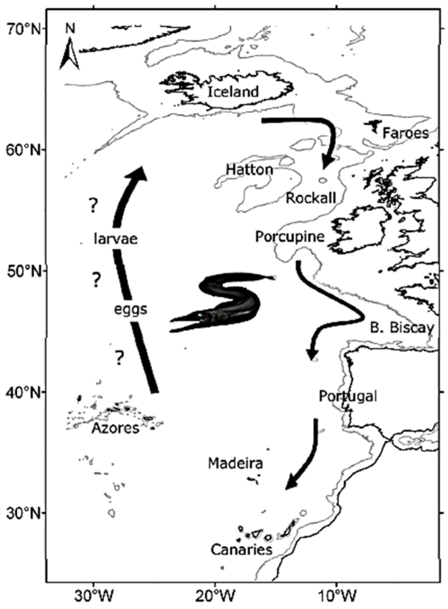


Figure 1.5. Proposed hypothetical migratory pattern of the black scabbardfish in the North Atlantic (from Farias *et al.*, 2013).

1.9.6. Diet

Unravelling the feeding ecology of a deep-water fish species can be exceedingly complicated due to the difficulties in obtaining samples (Santos *et al.*, 2013b), which usually are either regurgitated as a result of hydrostatic decompression or fully digested (Farias *et al.*, 2014). The black scabbardfish is a top benthopelagic predator and its diet is associated with prey with both pelagic and benthopelagic affinities. Many prey items are a part of its feeding portfolio, including crustaceans, cephalopods, shrimps and mesopelagic fish, blue whiting in particular, being perhaps the preferred prey (Santos *et al*, 2013a,b; Farias *et al.*, 2014). Hence, black scabbardfish forms a link between the pelagic and the benthopelagic food webs (Santos *et al.*, 2013b).

1.9.7. Fishery status

Over the past 10 years, black scabbardfish has been one of the main commercial deepwater species landed in Europe, making it one of the most important deepwater fish resources that are covered by the ICES Working Group on the Biology and Assessment of Deep-sea Fisheries Resources (WGDEEP) (Bordalo-Machado & Figueiredo, 2009; Bordalo-Machado *et al.*, 2009; Santos, 2013; Shon *et al.*, 2015).

There are three main deepwater fisheries targeting the black scabbardfish (or catching this species as bycatch) in the NE Atlantic (*Figure 1.6*): (i) to the west of the British Isles, which occurs mainly by the French trawl fishery, but more recently by the Faroese, Spanish and Icelandic fleets (Nakamura & Parin, 1993; Bordalo-Machado & Figueiredo, 2009; Santos, 2013); (ii) an artisanal fleet operates with bottom longlines in ICES Subarea IXa, off mainland Portugal (Bordalo-Machado & Figueiredo, 2009; Bordalo-Machado *et al.*, 2009; Santos, 2013); and (iii) an artisanal horizontal mid-water drifting longliners off Madeira Archipelago, within the FAO CECAF 34.1.2 area (*e.g.* Reis *et al.*, 2001; Bordalo-Machado *et al.*, 2001; Bordalo-Machado *et al.*, 2009; Gordo, 2009; STECF, 2014; SRA, 2014; Shon *et al.*, 2015). Also, the black scabbardfish fishery is present in the Azores Archipelago. It was developed in the 90's and since then, landings have risen, though not as expressive as in the other areas mentioned above (Machete *et al.*, 2011).

Considering a chronologic time window of the last 30 years, trends in black scabbardfish landings in northern areas is a falling pattern. From the beginning of 90s' until 2001, the landings of black scabbardfish from showed an accentuated increase, from 1023 tonnes in 1990 to 5057 tonnes in 2001. Since then, until 2005 the landings suffered a reduction to 2850 tonnes. Since 2006, in which a peak was registered of about 6527 tonnes, landings have been decreasing steadily, a scenario comparable to other deepwater fisheries (Santos, 2013; Farias *et al.*, 2013). Off mainland Portugal, an increasing trend was observed between 1988 and 1993, surpassing the 4000 tonnes barrier, followed by a slight decrease until 2000 of 2500 tonnes, and subsequently, landings have been stable around 2700-2500 tonnes per year, stabilizing at 2500 tonnes in 2015 (Bordalo-Machado *et al.*, 2009; Santos, 2013; Farias *et al.*, 2013; INE, 2015). In Madeira, the first decade was marked by an increasing trend from the 80's onward towards a maximum of 4430 tonnes recorded in 1998. The last time the barrier of the 4000 tonnes was reached was 2001. Since then, landings have been receding, reaching an all-time low of around 1700 tonnes in 2012 (not seen since 1984 when landings only reached 1086 tonnes), slightly increasing thereafter to roughly 1900 tonnes in 2015 (DREM, 2015a,b; Shon *et al.*, 2015). In the Azores, exploitation of this resource is still in its early days, being regarded as a nearly virgin exploited resource in the area (Machete *et al.*, 2011), thus landings recorded in the whole period was lower, reaching around 450 tonnes in 2012 (Farias *et al.*, 2013).

Figure 1.6. Some examples of the black scabbard fishing fleet from different regions; a) French deepwater trawlers at Lochinver port, Scotland (from Santos, 2013); b) Portuguese longliner from mainland Portugal (from palangreiro.blogspot.com); c) and d) "*São Álvaro*" and "*Alexandre Coelho*" vessels respectively, both Madeiran longliners. Differences are clearly visible. French vessels are larger and better equipped, while Portuguese vessels are much smaller, although the vessel from the mainland Portugal is somewhat similar in terms of construction material to the French vessels. Madeiran vessels are noticeably smaller, made out of wood, corresponding with the artisanal background of this fishery in Madeira (from the author).

1.9.8. Black scabbard fishery in Madeira Archipelago

Deepwater fishing is an ancestral fishing activity in the seas of Madeira and has, for the locals, a high historical, cultural and socio-economic value (Reis *et al.*, 2001; Gordo, 2009; ICES, 2014; SRA, 2014). This fishery, which particularly targets black scabbardfish [(currently it is now known that in fact the black scabbardfish catch include also the sympatric species, *Aphanopus intermedius*, Parin, 1983 (Biscoito *et al.*, 2011)] has centuries-old historical roots, in which its first historical records date back to the 17th century, and it is thought to have arisen as a result of the fishery of deepwater sharks (Merrett & Haedrich, 1997; Morales-Nin *et al.*, 2002; Gordo, 2009) Being emblematic of Câmara de Lobos town off which have arisen in nearby fishing grounds, subsequently irradiated to fishing areas scattered throughout the subarea of Madeira EEZ. Hence, the black scabbardfish fishery in Madeira waters has unique features, being one of the oldest fisheries exploitation of an abyssal resource globally (STECF, 2014; SRA, 2014).

Vessels that carry out fishing for this resource in Madeira EEZ are licensed for the use of a horizontal deepwater longline, which is locally known as "aparelho de espada" or “espinhel” (*Figure 1.7*) (Reis *et al.*, 2001; Bordalo-Machado & Figueiredo, 2009; STECF, 2014; ICES, 2014; SRA, 2014). The longline is a passive fishing gear, set in the water column, usually between 800-1200 meters deep in ocean fishing areas, each line having between 7000 and 8000 hooks, using steel nº 5 and nº 6 hooks (Bordalo-Machado & Figueiredo, 2009; SRA, 2014). The fishing of this resource is well developed, admittedly being a very selective fishing gear that captures adult black scabbardfish with very little capture and discards of non-target species (Bordalo-Machado & Figueiredo, 2009; STECF, 2014; ICES, 2014).

This segment of the fleet frequents mostly fishing areas in the north and south coasts of Madeira, Porto Santo and fishing grounds situated at considerable distances from the islands of the archipelago, namely several underwater seamounts such as the Seine, Lion, Unicorn, Dragon, Susanna and Ampère. Recently, especially since the second half of the past decade, some vessels of the fleet with greater autonomy began exploring fishing areas located off the subarea Madeira EEZ, particularly off the Canary Islands and underwater banks situated to the south of the Azores (Meteor Irving, Cruiser and Hyères) and inside the EEZ of that region (*Appendix B.3*) (STECF, 2014; ICES, 2014; Delgado *et al.*, 2016).

Operations regarding the fishing procedure usually start at dusk following a well-defined pattern: vessels leave port early at sunset, carrying a previously equipped longline equipment (at present, the preparation of the gear is still entirely done by hand) (Bordalo-Machado & Figueiredo, 2009), heading offshore for a period that can take several hours (contingent on the vessels’ engine power, velocity and location of the fishing ground). When the vessel is at the fishing ground, two fishing operations generally follow: the longline gear is deployed into the water and set, and another longline gear previously set in the last 24–48 hours is recovered with the aid of a hauling winch installed on board (Bordalo-Machado & Figueiredo, 2009; ICES, 2014). The occasional occurrence of cetaceans, can result in a significant economic cost for the fishermen as these marine mammals are attracted by the catch when it reaches the surface and feed on the fish caught (ICES, 2014).

Until recently, *A. carbo* was the only recognized species in this genus, although several other junior synonyms were described (Nakamura & Parin, 1993; Biscoito *et al.*, 2011). In 1983, a description of *A. intermedius*, partially sympatric with *A. carbo*, was published and now the genus *Aphanopus* comprises seven species distributed throughout all oceans except in the Polar Regions and the Mediterranean Sea (Parin, 1995).

For fisheries purposes, these two species have been treated as *A. carbo* in Madeira and subsequently, landing statistics and fisheries research prior to 2010 refer to a combination of these two species (Biscoito *et al.*, 2011).

Much less prevalent, *A. intermedius* represents 20% of total catches (Delgado *et al.*, 2013), and it is worthwhile pointing out that the main variables by which *A. carbo* may be separated from *A. intermedius* (dorsal fin and vertebral counts; Nakamura & Parin, 1993; Parin, 1995; Biscoito *et al.*, 2011) are rather difficult to use in the field and are entirely inappropriate for large scale fisheries-purpose identification, on board vessels or at landing sites (Biscoito *et al.*, 2011).

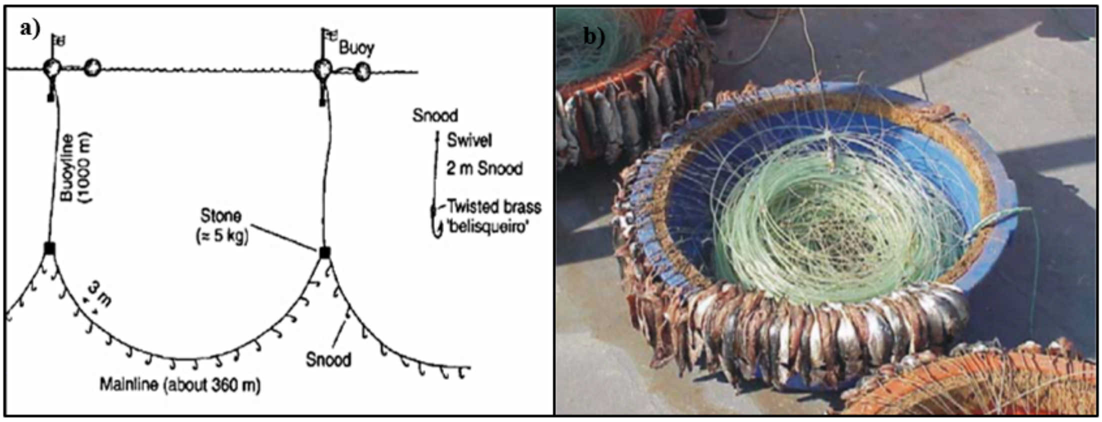


Figure 1.7. Fishing gear used in the black scabbard fishery; a) schematic of the horizontal drifting mid-water longline used to capture *A. carbo* in Madeiran waters (from Reis *et al.*, 2001); b) black scabbard fishing gear prepared around a large bucket and ready to be deployed (from the DSI archives).

1.10. Thesis general objectives

Since the very beginning, where Richard Thomas Lowe, an English naturalist, identified this specie as *Aphanopus carbo* back in 1839, it has always sparked scientists' minds. In the 50's, Günther Edmund Maul, a German ichthyologist and taxidermist, continued the work of R. T. Lowe. Maul (1950) was published and subsequent publications followed in the 60' and 70's, setting the cornerstone for future investigations, still admired to this very day. Magnusson, J., continued to draw attention on the matter by studying this species in Icelandic waters, Parin, N. V., responsible for identifying *A. intermedius* in 1983, John D. M. Gordon with his worldly known publications, and more recently the likes of Ivone Figueiredo from IPMA, Portugal, Pedro Bordalo-Machado from IPMA, Portugal, professor Leonel S. Gordo fom the University of Lisbon, Manuel Biscoito, Director of the Science Department of the Municipality of Funchal, João Delgado from the Director of the ‘Serviços de Investigação da Direção Regional de Pescas’ of Madeira, among many others who contributed to an ever-increasing knowledge of this species.

Several other research projects have been developed throughout the years focusing on black scabbardfish. The project BASBLACK (1998-2000) studied the biology of black scabbardfish in which several management strategies were withdrawn from it. Another highly referenced project focusing on *A. carbo* was the APHACARBO project. Its mains goals were centred on the identification of the stock structure(s) through a combination of methodologies, and also on the assessment of the biochemical composition and bioaccumulation levels to assure fish quality with respect to EU standards (Gordo, 2009).

In these last decades many research endeavours took place and it is following the footprints of those works that this study is leaned upon. The general concerns about the sustainability of deepwater resources and the urgent need to continue to enhance our understanding of this resource constitute the basis for this study. In this context, the proposed objectives are as follows:

1) Study the biology of *Aphanopus carbo*, based on specimens landed in Funchal harbour from 2010 to 2015. Although identified as black scabbardfish upon landing, posterior analysis makes possible to identify if it is *A. carbo* or *A. intermedius*. Thus, this study focuses only on *A. carbo*, and leans upon on subjects such as population structure, sex ratios, reproductive cycle through gonad and liver indexes, condition factor, length at first maturity through maturity ogives and morphometric relationships (WLRs and LLRs).

2) Perform a standardization of landings-per-unit-effort (LPUE) data series of Madeira Archipelago, covering the period of 2008-2015. The data is part of the ‘Programa Nacional de Recolha de Dados de Pesca’ (PNRDP), in which commercial-based statistics is gathered for management purposes for all exploited commercial species. Differently from the previous analysis, here the data will cover both sympatric species, *A. carbo* and *A. intermedius*, since they are not differentiated for commercial purposes, being referenced henceforth in this chapter as *Aphanopus spp*. The purpose is to understand the factors affecting the fishery of *Aphanopus spp.* in Madeira Archipelago, and possibly to increase the awareness for better management strategies.

1.11. Thesis structure

This thesis is divided in two parts. The first part will cover the biology of *A. carbo* and the second the standardization procedures and abundance-related issues of *Aphanopus spp.*, described previously in the objectives. Each chapter constitutes a complete study, and in each one, an introduction on the subject is followed by thorough explanation of the methodology, and subsequent results and conclusions. Lastly, a general conclusion was made covering all topics of the thesis, in a succinct approach.

Chapter 2

Biology of black scabbardfish (*Aphanopus carbo* Lowe, 1839) in Madeira Archipelago, Portugal

1. Introduction

Field sampling programs provide the information needed to determine the status and dynamics of marine populations and communities, providing the basis for many kind of fisheries research projects. The physical, biological complexity and dynamism of most marine ecosystems result in high spatial and temporal variability in almost any measured parameter. Considering that a proper assessment and management of a fishery requires an understanding of the biology, life cycle and distribution of a species (King, 1995), the sampling methods and procedures need to be carefully analysed and selected in order to take into account this high variability of most marine systems. Thus, the description of biological parameters, examining fisheries landings, *i.e.*, fishery-dependent data, or examining data collected from resource surveys which are specifically designed to follow consistent and unbiased methods, *i.e.*, fishery-independent data, is fundamental to comprehend any given species' idiosyncrasies (Haddon, 2001).

Total length, total weight, sex identification, sexual maturity stage, among other biological traits constitute absolute requirements for the study of a species' population dynamics, for evaluating fishery sustainability and to assess stocks. Biometry features, when collected, provide the tools for the correct calculation of a series of appropriate indexes, *i.e.*, proxies, to infer about the state of the population (King, 1995; Pajuelo *et al.*, 2008; Neves *et al.*, 2009). Regarding the previous considerations, several analyses form the backbone of fisheries biology, physiology and ecology studies (Santos *et al.*, 2002).

One of the most commonly used in any analysis in fishery data is the weight-length relationship (WLR) simply because, in fishes, size is generally biologically more relevant than age, since several ecological and physiological factors are more size-dependent than age-dependent (Santos *et al.*, 2002). WLRs, depicted as $W = aL^b$ (Ricker, 1975), where b is the slope of the log-transformed relation and a is the intercept, are based on the premise that fish growth can be exhibited in two ways: isometrically ($b = 3$) where weight increases proportionally with length, or allometric ($b < 3$ – negative allometry; $b > 3$ – positive allometry) where body size increases disproportionately to weight (Froese, 2006; Froese *et al.*, 2011). WLRs have a number of applications including: (i) the estimation of weight from a given length and estimation of standing-crop biomass when length-frequency distribution is known, particularly useful since weighting an individual at sea is unpractical and hardly precise due to the ships' constant movement (King, 1995); (ii) conversion of growth-in-length equations to growth-in-weigh for prediction of weight-at-age (Pauly, 1993); (iii) calculation of condition indexes (Petrakis & Stergiou, 1995); and (iiii) life history and morphological inter-species comparisons, or intra-species comparisons between fish populations from different geographical regions (King, 1995; Petrakis & Stergiou, 1995; Gonçalves *et al.,* 1997; Santos *et al.,* 2002; Froese, 2006; Hossain *et al.,* 2006). Equally relevant are the length-length relationships (LLRs), where estimation can be based upon WLRs, in which the slope revolves around isometry ($b = 1$) or allometry ($b > 1$ - positive allometry or $b < 1$ - negative allometry) (Ali *et al.,* 2013; Keskar *et al.,* 2015). These are also very useful in fisheries management for comparative growth analysis (Moutopoulos & Stergiou, 2002; Froese, 2006; Hossain *et al.*, 2006). Thus, both WLRs and LLRs are an important component of fisheries biology and when properly calculated, can be valuable to fisheries management efforts (Froese *et al.,* 2011).

Closely related to WLRs is the Fulton's condition factor (Froese, 2006; Nash *et al.*, 2006), dating back to 1911 and, since 1975, used henceforth by William E. Ricker and other authors based on the former (Nash *et al.,* 2006). Widely used in fisheries and general biology studies, it bases on the assumption that heavier fish of a given length are in better condition (nutritional and health status; Froese, 2006). This factor is calculated from the relationship between weight and length, with the intention of describing the condition of an individual. The formula is depicted as: $K = 100\ (W/L^3)$ (Ricker, 1975) where K is the Fulton's condition factor, W is the weight, and L is the length of the fish (Froese, 2006; Nash *et al.,* 2006).

The interpretation of the condition factor is difficult and prone to error. This equation assumes that the WLR is isometric in nature, in which $b = 3$, and since not all fish grow isometrically, other variations from this equation were made in order to accommodate different growth patterns (Richter *et al.,* 2000; Froese, 2006). Accordingly, to reduce or eliminate these effects from that estimation, the calculation of the condition factor has been proposed as: $K' = 100\ (W/L^b)$, where b, from the WLR, is the determining factor behind a specimen's condition (Richter *et al.,* 2000). This nuance, designated as the allometric condition factor (K'), introduced by Tesch (1968), best fits for comparing individual specimens across populations or species. This variant is to be used when a large and representative body of data is available for an allometrically-growing species so that a sufficiently accurate value of b can be computed (Froese, 2006).

The previous variation differed from Le Cren's (1951) calculation of relative condition, proposed as: $K_{rel} = W/aL^b$, by omitting the coefficient a from the equation. The relative condition factor compensates for changes in form or condition with increase in length, and thus measures the deviation of an individual from the average weight for length, that is, the assumption that fish grows as much as in weight as in length (Richter *et al.*, 2000; Froese, 2006). This allows for comparison of the condition of different specimens within a sample, independent of length, although not allowing comparisons across populations. Although conferring greater flexibility, K' does bring drawbacks due to the volatility of *b* which can vary contingent on species, location, size, and other circumstances. The main concern relates to the difficulty to obtain a reliable value of *b*, particularly if the data set is small or does not span a wide enough range of body lengths (Richter *et al.*, 2000; Froese, 2006).

Other variations were made in order to adapt the estimation of the condition factor to the particularities of any given sample. Regardless of the equation, the characteristics of the sample will always determine the best estimation of body condition. All things considered, the condition factor provides information on the variation of fish physiological status and may be used for comparing different populations or individuals from within the same population living in certain feeding, climate and other conditions as it can denote seasonal and overall 'well-being' of fish, making it an important tool for fisheries biologists (Richter *et al.*, 2000; Froese, 2006; Hossain *et al.*, 2006).

An intrinsic part of fisheries or any biology study relates to the collection and analysis of relevant reproduction parameters, fundamental for understanding and predicting population dynamics scenarios for management purposes. A variety of reproductive traits, from maturity stage, to gonads and liver weight, is widely used to provide information to depict a species' reproductive cycle, time and geographical location of spawning, sex ratio, migratory patterns linked to reproduction, and among others (Neves *et al.*, 2009).

A review of reproductive characteristics relies on the accurate estimation of gonadal development and determination of maturity stages in individual fish. Determination is based either on a macroscopic examination or on a more accurate histological analysis of the gonad (Kokokiris *et al.*, 2014). Moreover, sex ratio is also important to provide information on the population structure in terms of sex. It states the proportion of male to female individuals in a population and indicates the dominance of a given sex in the population. Sex ratio also constitutes basic information necessary for the assessment of the potential of fish reproduction and stock size estimation in fish population (Hamilton, 1967).

Body indexes have been used as indicators of change in nutritional and energy status of fish. The gonadosomatic index (GSI), an index of gonad weight relative to fish weight, is a good indicator of gonadal development in fishes (Dadzie & Wangila, 1980). The percentage of body weight of the fish that is used for production of eggs is determined by the gonadosomatic index. GSI has been widely used to evaluate reproduction timing (Lowerre-Barbieri *et al.*, 2009) as it is easy to compute and analyse. Changes in GSI are mostly determined by variations in yolk concentration during different oocyte stages and thus it provides information about maturation and seasonal patterns in regards to the characteristics of the reproductive cycle (West, 1990). The hepatosomatic index (HSI) assumes the same nature as GSI. It is an index of liver weight relative to body weight. HSI is associated with liver energetic reserves and metabolic activity since it is a vital organ responsible for various physiological functions, such as the conversion of excess sugar into glycogen, detoxification of toxic substances, acts as haematopoietic organ, and others (Dorcas & Solomon, 2014).

Another important population attribute is the proportion of mature individuals at age or length. Generally designated as maturity ogive, it directly relates to the reproductive potential of the population, being particularly relevant in terms of exploited fish populations, since it determines the spawning biomass upon which conservation measurements are usually based (Flores *et al.*, 2014). It consists of three steps: (i) identification of the spawning season, mostly done by analysing GSI throughout the year; (ii) maturity stages must be attributed; (iii) observed proportions of mature/immature per length or age are used to compute length or age at maturity through a logistic function. Length (L_{50}) or age (T_{50}) at sexual maturity is then attained, defined as the length or age in which 50% of the sample has reached sexual maturity (Roa *et al.*, 1999; Flores *et al.*, 2014).

The choice of applying one method over other, ultimately depends on the variables to be measured, the source and the actual resources available. Different variables require different approaches, each varying contingent on the type of fishery, data and on the objective intended. A large period over a great part of the intended area to be analysed should be covered to grant a better insight in terms of a species reproductive cycle, population structure and migratory patterns (FAO, 1998). Regarding this study, all measures and precautions were taken to guarantee that both data collection and analysis were performed according to known standards in the fisheries biology field, always applying commonly used techniques. It relies on fishermen, government officials, and general staff, which ensures that the fishery industry in Madeira archipelago remains properly regulated. Ultimately, this work will continue to strengthen the foundations in which marine biota, in this part of the Atlantic, remains healthy and in a flourishing state.

Consequently, the objective of this chapter is to perform a bibliographic revision regarding the biology of *A. carbo* in Madeiran waters. Topics covered are as follows:

1) Characterize the population structure;

2) Study the reproductive cycle of this species, by means of:

- Attributing maturity stages through macroscopic analysis of the gonads;
- Sex ratio determination in regards to length class and month;
- Calculating gonadosomatic and hepatosomatic indexes to have a clear perspective on the reproductive cycle throughout the year;
- Estimating the condition factor;
- Determining length at maturity by fitting maturity ogive;

3) Determination of WLR and LLR.

2. Materials and methods

All sampled individuals were caught by the Madeira black scabbard fishing fleet. All fishes were landed in Funchal harbour, and on a routine weekly basis, around 30 individuals would be taken randomly from the commercial mid-water drifting longline fishery operating in Madeira, and brought back to the fisheries laboratory at the 'Direção dos Serviços de Investigação da Direção Regional de Pescas da RAM' (DSI) at Funchal harbour to be studied. Considering the total sample size, it is comprised of 3112 individuals, from January, 2010 to December, 2015, which 1626 are females, 1480 are males, 3 are undifferentiated and 3 others were not classified in respect to sex. As it is understandable, especially for a sample this size, some individuals lack in biological data, such as total length or standard length, gonad weight or liver weight, and what one lacks in one variable, others lack in other, which is the reason the sample size varies according to the type of analysis performed.

Since in NE Atlantic waters *Aphanopus carbo* (Lowe, 1839) and *Aphanopus intermedius* (Parin, 1983) live in sympatry and share very close morphological resemblance, a procedure is performed following the study carried out by Biscoito *et al.* (2011) to ensure the correct description of each individual according to species. If none of the features were enough to render a correct classification, the individual would be given the classification of the genus *Aphanopus spp.*

Considering that the knowledge of the two species of black scabbardfish that live in sympatry in NE Atlantic waters is recent (Biscoito *et al.*, 2011), up to 2010, both species were landed and biologically examined as one. Prior to 2010, both species, *A. carbo* and *A. intermedius*, were studied as one and designated as *A. carbo*, rather than *Aphanopus spp.*, in which its broader spectre would include both species. Hence, this thesis focused on data from 2010 onwards, up to 2015, the most recent data collected in result of the aforementioned circumstance. A five-year period is covered and, apart from occasional time periods where no sampling took place due to several reasons, especially in the second semester of 2012 and in the first three quarters of 2013, the data shown best describes the biology of black scabbardfish in this part of the Atlantic. In succinct, the biological sampling consisted in data referring to:

- Total length and standard length (defined as the length from the most anterior part of the fish to the most posterior point, where the body ends and the caudal fin rays begin): precision to 0.1 cm;

- Total weight and eviscerated weight: precision to 1 g;

- Sex was determined through macroscopic examination of the gonads as: female, male or unsexed (due to extremely low numbers, unsexed individuals were not considered in any analysis);

- Maturity stage: macroscopic analysis, from 1 to 5 (immature, developing/recovering, spawning capable, actively spawning and regressing) according to definitions provided by Gordo *et al.* (2000);

- Gonadal and liver weight: precision to 0.1 g;

- Sagittal otoliths are removed, cleaned and placed in labelled plastic containers with alcohol for posterior analysis;

- A presence/absence analysis of parasites is performed in the gonads, muscular tissues, digestive tract and around the abdominal cavity: scaled from 1 – slightly present, 2 - moderately present, 3 – heavily present;

- Differentiation between *A. carbo* and *A. intermedius*: counting dorsal fin rays and vertebrae according to Biscoito *et al.* (2011);

- Analysis to detect and quantify, if existent, the presence of mercury (Hg+): muscular tissue and gonad tissue is removed for latter analysis.

Additionally, although it is referred as part of the methodology, age estimation was not done. Age reading through otoliths was not performed as well it was not included the contaminants analysis as well, specifically to mercury (Hg+). As part of the data treatment, Microsoft Excel was used to manage the raw data, to perform regressions through the supplement Analysis ToolPack (VBA), and to plot graphics. Statistical tests were almost entirely performed using the software RStudio, an integrated software of R version 3.2.2 (R Core Team, 2015). In all statistical tests, a significance level of 5% was applied (α = 0.05). Each type of data treatment will be comprehensively referred and explained individually in subsequent topics.

2.1. Population structure

Length and weight were plotted, in 5 cm length class and in 100 g weight class respectively, discriminating females from males. With regards to this analysis, a total of 3105 individuals were assessed in terms of weight and 2900 in terms of length. A parametric *student's t-test* was applied after normality was assured, in order to assess if significant differences were found in length and weight frequencies between females and males (Morato *et al.,* 2001; Palazón-Fernandez *et al.*, 2001; Pajuelo *et al.*, 2008; Rochon *et al.*, 2012).

2.2. Reproduction

2.2.1. Maturity stages

The sexual maturity stages of black scabbardfish in known bibliography was previously assessed by Gordo *et al.* (2000) and are described here in *Table 1*. Also, the monthly distribution for both sexes according to the maturity stages are presented in *Table 2.1*.

Table 2.1. Macroscopic descriptions of the phases in the reproductive cycle of both female and male of *A. carbo* from Gordo *et al.* (2000).

Maturity stage	**Stage description**	**Macroscopic description**
Female		
I	**Immature**	Ovaries small, translucent or light pink; oocytes not visible macroscopically.
II	**Developing**	Ovaries opaque, generally slightly pink. The oocytes can be seen with the naked eye, as small punctuations spread all over the gonad.
III	**Pre-spawning**	Ovaries yellowish or pinkish in colour with a clear vascularization. Large oocytes easily distinguishable.
IV	**Spawning**	The ovaries occupy the entire abdominal cavity. Ovarian membrane very thin, easily ripened.
V	**Post-spawning**	Ovaries flaccid; reddish in colour with residual eggs.
Male		
I	**Immature**	Firm testes with laminar aspect, translucent.
II	**Developing**	Testes white-pinkish in colour and larger than previous stage.
III	**Pre-spawning**	Testes white in colour, occupying a large portion of the abdominal cavity. Sperm can be extruded after pressure on the abdomen.
IV	**Spawning**	Testes white and full of sperm. Sperm is easily extruded after slight pressure.
V	**Post-spawning**	Testes flaccid with a haemorrhagic aspect. Residual spermatozoa.

2.2.2. Sex Ratio

The global sex ratio (number of males/number of females) was determined and a Pearson's Chi-squared test (χ^2) at a significance level of 95% was used to test whether observed sex ratios were significantly different from the expected ratio of 1:1 (Pajuelo *et al.,* 2008; Delgado *et al.,* 2013; Santos *et al.,* 2013a). Hypothesis 2.1 was formulated based on the previous statement as:

$$H_0: p_{♀} = p_{♂} \text{ vs } H_A: p_{♀} \neq p_{♂} \qquad \text{(Hypothesis 2.1)}$$

in which,

H_0: proportion of females is equal to the proportion of males (1:1);

H_A: proportion of females is not equal to the proportion of males.

Null hypothesis was rejected if the following assumption was fulfilled: $\chi^2 > \chi^2_{0.05;1} = 3.84$, in which χ^2 represents the observed value and $\chi^2_{0.05;1}$ represents the table value for $\alpha = 0.05$ and 1 degree of freedom from the chi-squared distribution table (Montgomery, 2013). The test was used for the entire sample, and also for subsets divided by month, as shown in *Table 3.1,* and by 5 cm length class as shown in *Table 4.1.*

2.2.3. Gonadosomatic and Hepatosomatic indexes

The monthly evolution of the gonadosomatic index (GSI), described in Equation 2.1, is often used to follow a species' reproductive cycle. Characterization of the spawning season was made by analysing the monthly distributions of the percentage frequency of gonad maturity stages and confirmed by the evolution of the mean monthly GSI. Expressed by gonad weight as a percentage of total weight (King, 1995), Equation 2.1 describes GSI as follows:

$$GSI = 100\,(G_W/T_W) \qquad \text{(Equation 2.1)}$$

in which,

G_W: gonad weight (g);

T_W: total weight (g).

Similarly, the hepatosomatic index (HSI), described in Equation 2.2, which expresses liver weight as a percentage of total weight (King, 1995), can be defined as:

$$HSI = 100\ (L_W/T_W) \qquad \text{(Equation 2.2)}$$

in which,

L_W: liver weight (g);

T_W: total weight (g).

A Spearman correlation, which evaluates if the variables tend to change together, but not necessarily at a constant rate (Hauke & Kossowski, 2011), was performed between GSI and TL in females, to determine if length and sexual maturation are correlated. Furthermore, GSI and HSI were tested for presence/absence of correlation for both sexes to infer about the relationship of both variables in the sexual cycle (Palazón-Fernández *et al.,* 2001).

Mean monthly values of GSI and HSI were computed and plotted to ascertain monthly variations amongst males and females (Santos *et al.,* 2013a). Mean values of those variables were plotted with maturity stages per sex in order to ascertain the relationships between these variables in the reproductive cycle of this species (Neves *et al.,* 2009; Gomiero *et al.,* 2010; Santos *et al.,* 2013a). Also, GSI were tested if significant differences exist with total length.

The variation of these indexes was analysed using a parametric test *one-way analysis of variance* (ANOVA) – after assuming that the errors are normally and independently distributed by histogram analysis of the data and ensuring equality of variances (homoscedasticity) by graphic reconnaissance of the residuals vs. fitted values (*Appendix A.1*) (Palazón-Fernández *et al.,* 2001; Neves *et al.,* 2009; Zuur *et al.,* 2009; Rochon *et al.,* 2012). Therefore, Hypothesis 2.2 was designed following suggestions of Montgomery (2013), as follows:

$$H_0: \mu_1 = \mu_2 \quad \text{vs} \quad H_A: \mu_1 \neq \mu_2 \qquad \text{(Hypothesis 2.2)}$$

in which,

If $\mu_1 = \mu_2$ means are equal;

If $\mu_1 \neq \mu_2$ means are not equal;

The null hypothesis is rejected if $F_0 > F_{\alpha}, a - 1, n - a$.

2.2.4. Length at maturity

Length at first maturity (L_{50}), *i.e.*, length in which 50% of the individuals sampled are sexually mature, was determined by fitting maturity ogives (Equation 2.3). The percentages of mature individuals per length class (1 cm) were estimated for males and females. Specimens in stage I were considered immature and individuals in subsequent stages (II, III, IV, V) were considered mature. Due to low numbers of immatures individuals, a clear transition between immature and mature was not present. Instead, an abrupt change was verified. Therefore, a knife's-edge approximation was performed, stating that all individuals smaller than L_{50} are immature (King, 1995). The values presented were gathered from 2010 to 2015. L_{50} was calculated using data from the last quarter of the year which corresponds to the spawning period, determined according to the monthly changes in the percentage frequency of the maturity stages and the value of the gonadosomatic index (West, 1990). The spawning period referenced previously is also consistent with previous studies revealing that the spawning period spans from September to December (*e.g.* Figueiredo *et al.*, 2003; Neves *et al.*, 2009; Santos *et al.*, 2013a). A logistic curve was fitted to the data and total length at which 50% of the individuals are sexually mature was calculated using Equation 2.3 (Bordalo-Machado *et al.,* 2001; Figueiredo *et al.,* 2003), as follows:

$$P = 1/[1 + e^{-(a + bL)}] \qquad \text{(Equation 2.3)}$$

in which,

P: proportion of mature individuals at length L;

a and b: model parameters from the linear regression.

The parameters estimation of the maturity ogives was performed using a linear regression model through the least-square method. The mean length at sexual maturity was calculated as $L_{50} = -a/b$ (King, 1995). In addition, a summary on length at first maturity obtained by other authors for this species is presented in *Table 5*.

2.3. Weigh-Length and Length-Length Relationships

The WLR was performed including all individuals from both sexes separately and combined. Total sample size was composed of 2895 individuals, of which 1522 were females and 1373 were males. The WLR, described in Equation 2.4, is as follows (Ricker, 1975):

$$W = aL^{b} \qquad \text{(Equation 2.4)}$$

in which,

a: intercept and linear coefficient;

b: slope or allometry coefficient;

L: length of a given specimen (cm);

W: weight of a given specimen (g).

The model parameter a was obtained by the function [exp (a)] from the intercept of the regression, and the model parameter b was obtained using a linear regression through the least squares method, applied in log-transformed data (King, 1995; Montgomery, 2013).

The adherence of the empirical points was analytically demonstrated by calculating the coefficient of determination (r^2) to assess the degree of association between variables, or the quality of the linear regressions (Froese, 2006). Before fitting the linear regression, the log-transformed data was plotted and obvious outliers, attributed to measurement error or any other factors were removed before fitting the regression (Froese *et al.*, 2011).

In order to verify what type of relationship does total weight have with total length, Hypothesis 2.3 was formulated to test such relationship, shown as follows (Froese, 2006):

$$H_0: b = 3 \ \text{ vs } \ H_A: b \neq 3 \qquad \text{(Hypothesis 2.3)}$$

in which,

H_0: specimens exhibit isometric growth;

H_A: specimens exhibit allometric growth.

The *b*-value was tested by the parametric test *student's t-test*, with a significance level of 5%, as shown in Equation 2.5, in order to verify if it differed statistically from the isometric value of 3 ($b = 3$). The test was performed by the following equation (Montgomery, 2013):

$$t_s = b - \beta_0 / S_b \qquad \text{(Equation 2.5)}$$

in which,

$t_{s:}$ value of the *t-test*;

b: slope or allometry coefficient from the WLR;

β_0: *b*-value to be tested;

S_b: standard error of the curve (b).

The 100(1 - α)% confidence interval (*CI*) of parameter *b*, shown in Equation 2.6, including upper and lower limits was calculated as follows (Haddon, 2001; Montgomery, 2013):

$$CI = b \pm [(t_{\alpha/2,\, n-a} \sqrt{MS_E/n}) \text{ x } S_b] \qquad \text{(Equation 2.6)}$$

in which,

CI: confidence interval;

b: sample parameter estimate (slope or allometry coefficient from the WLR);

$t_{\alpha/2,\, n-2}\sqrt{MS_E/n}$: *student*'s *t*-distribution value for n - a degrees of freedom (*df*) for a treatment, $\alpha/2$ is the percentage confidence limits desired, with $\alpha = 0.05$, 100(1 - α)% providing the 95% interval, where $\alpha/2$ = 2.5% and 97.5% ($-1.96 < t < 1.96$). The 1.96 is the critical value from the 95% confidence interval; MS_E/n is the mean standard error of the regression;

S_b: standard error of the curve (b).

The comparison between the obtained *t*-value with the known *t*-distribution value from the table allowed to determine the statistical significance of *b*-values, including it into the isometric interval ($b = 3$) or allometric range (negative allometry $b < 3$, or positive allometry b

> 3) (Froese, 2006; Froese *et al.,* 2011). All *b*-values within the confidence interval ($-1.96 < t < 1.96$), are considered isometric in nature, hence accepting the null hypothesis, which in turn suggests that specimens increase evenly in weight as they increase in length. Conversely, *b*-values that fall off the interval, are considered allometric in nature, hence rejecting the null hypothesis, revealing that increment of weight is made unevenly as length increases (Froese, 2006; Froese *et al.*, 2011).

The description of the WLRs characteristics is shown in *Table 6* and in *Table 7*, the latter containing the results obtained in this study and in other studies in different geographical locations.

Similarly, LLRs were performed. Total sample was composed of 2697 individuals, of which 1386 were females and 1311 were males. Through Equation 2.7, LLRs were estimated as follows (Froese, 2006; Ali *et al.,* 2013; Keskar *et al.,* 2015):

$$\mathrm{TL} = a\mathrm{SL}^b \qquad \text{(Equation 2.7)}$$

in which,

TL: total length;

SL: standard length;

a: intercept and linear coefficient of the LLR;

b: slope or allometry coefficient of the regression.

Goodness of fit was determined by r^2, following the same criterions as described for WLRs. In order to verify what type of relationship does total length have with standard length, Hypothesis 2.4 was formulated to test such relationship, shown as follows (Froese, 2006):

$$H_0: b = 1 \text{ vs } H_A: b \neq 1 \qquad \text{(Hypothesis 2.4)}$$

in which,

H_0: specimens exhibit isometric growth;

H_A: specimens exhibit allometric growth.

A Pearson correlation, which evaluates the linear relationship between two continuous variables (Hauke & Kossowski, 2011), was performed between both variables to test if a change in one variable is associated with a proportional change in the other variable.

The *b*-value was tested by the parametric test *student's t-test*, with a significance level of 5%, as shown in Equation 2.5, in order to verify if it differed statistically from the isometric value of 1 ($b = 1$) (Ali *et al.*, 2013; Keskar *et al.*, 2015). The $100(1 - \alpha)\%$ confidence interval of b was obtained using Equation 6, thus following the same procedure as done in WLRs.

Regarding the model parameters of the LLR, *b*-values within the confidence interval ($-1.96 < t < 1.96$) indicate isometry, accepting the null hypothesis, *i.e.*, increase in total length of the fish is proportional to the increase in length of the caudal fin, and *b*-values outside the confidence interval indicate allometry, accepting the alternative hypothesis, *i.e.*, with the increase in length of the fish, the caudal fin does not increase proportionally but grows with lesser increments (Ali *et al.*, 2013; Keskar *et al.*, 2015). Furthermore, the description of the LLRs parameters is shown in *Table 8*.

2.4. Condition factor

Fulton's proposed the use of a mathematical formula for quantifying or estimating the condition of fish. The role of the condition factor is to quantify the healthiness of individuals. It is based on the hypothesis that heavier fish of any given length are in better condition, and therefore, have better chances to generate more offspring, *i.e.* increase their fitness (Froese, 2006). The generic equation, as shown in Equation 2.8, is described as follows (Ricker, 1975):

$$K = 100\ (T_W/T_L^3) \qquad \text{(Equation 2.8)}$$

in which,

K: Fulton's condition factor;

T_W: total weight (g);

T_L^3: total length (cm) to the power of 3, following an isometric growth.

This equation assumes isometric growth, though it has been shown that fish often grow allometrically, with the rate of allometry changing between different growth "stanzas" (Froese, 2006). Since not all fish species grow isometrically, to assume $b = 3$ in the calculation of the condition factor is to introduce a bias in the estimation (Richter *et al.,* 2000). Therefore, not only to eliminate these effects, but also considering that the objective of this study is to compare the condition of different specimens from the same sample, the estimation of the condition factor was performed using Le Cren's (1951) relative condition factor, described in Equation 2.9, as follows:

$$K_{rel} = W/aL^{b} \qquad \text{(Equation 2.9)}$$

in which,

K_{rel}: relative condition factor;

W: total weight (g);

L: total length (cm);

b: slope or allometry coefficient of the regression from the WLR;

a: intercept and linear coefficient of the WLR.

A Spearman correlation was performed between K_{rel} and GSI, and between K_{rel} and HSI for both sexes, to determine if a relationship exists between the sexual seasonal cycle and physiological status.

A similar analysis as the one used for GSI and HSI was performed. Mean monthly values of K_{rel} were computed and plotted to ascertain monthly variations amongst males and females (Santos *et al.,* 2013a). Mean values of those variables were plotted with maturity stages per sex in order to ascertain the relationships between K_{rel} with GSI and HSI (Neves *et al.,* 2009; Gomiero *et al.,* 2010; Santos *et al.,* 2013a).

The variation of these indexes was analysed using a parametric test *one-way* ANOVA, after assuming that the errors are normally and independently distributed by histogram analysis of the data and ensuring equality of variances (homoscedasticity) by graphic reconnaissance of the residuals vs. fitted values (*Appendix A.1*) (Palazón-Fernández *et al.,* 2001; Neves *et al.,* 2009; Rochon *et al.,* 2012). Following the same criterions as used for GSI and HSI, Hypothesis 2.2 was tested and conclusions were made based on the results.

3. Results

3.1. Population structure

Length and weight distributions of *A. carbo* landed in Madeira are presented in the following figures. Fish varied from 88.7 to 148.2 cm in total length (*Figure 2.1a*) and between 1048 to 4122 g in total weight (*Figure 2.1b*). In females, total length ranged from 94.7 to 148.2 cm and total weight ranged from 1101 to 4122 g, whether in males, the total length distribution ranged from 88.7 to 142.5 cm and the total weight ranged from 1048 to 3662 g. Results of the *t-test* indicated significant differences in length (t = -25.19, df = 2875.3, $p < 2.2e^{-16}$) and weight (t = -27.854, df = 3004.9, $p < 2.2e^{-16}$) frequency distributions between females and males. A clear trend is seen as females are the largest and heaviest and males are the smallest and lightest individuals.

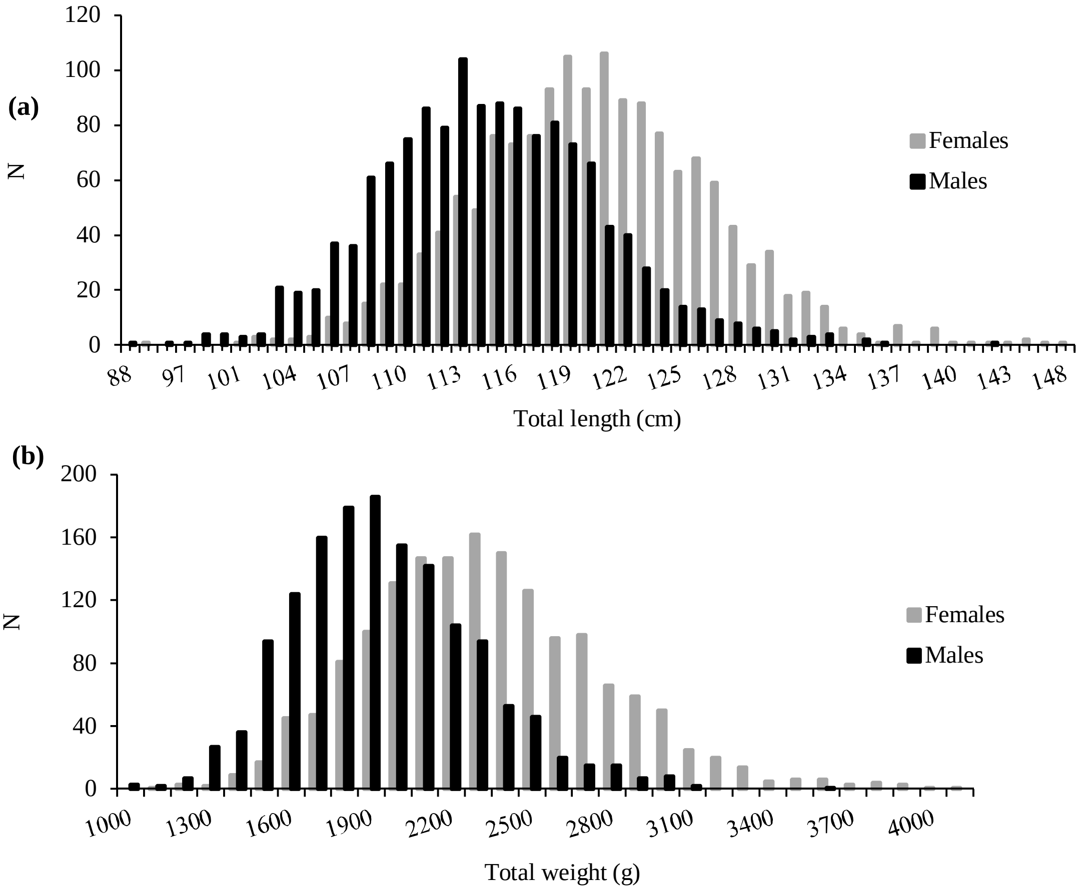


Figure 2.1. Length-frequency (a) and weight-frequency (b) distribution for each sex of *A. carbo* caught in Madeiran waters from 2010 to 2015.

3.2. Reproduction

3.2.1. Maturity Stages

Sample size consisted of 3050 individuals, 1592 females and 1458 males (*Table 2.2*). All maturity stages were observed in both sexes. Immature individuals (stage I) were the least common stage with only 11 specimens present (1.6%), as expected, since Madeira waters are a spawning ground for *A. carbo*, hence larger and mature individuals prevail in this area. Mature individuals comprised the most significant part of the population sampled, with 1246 (37.52%) in stage II (818 females and 428 males), stage III had 884 (23.6%) specimens (259 females and 625 males), stage IV had 177 (9.29%) individuals (91 females and 86 males) and lastly, stage V had 732 (27.99%) individuals (420 females and 312 males).

The most representative maturity stage is stage II. A distinct transition can be seen in which stage II gives way to stage IV and V in latter stages of the year, and stage V dominates across both sexes after the spawning season, especially after December, dominating in December until March (*Figure 2.2*).

Table 2.2. Sample distribution according to maturity stages on a monthly basis of specimens of *A. carbo* caught in Madeiran waters from 2010 to 2015.

Months	**Maturity stages**										**Total**
	I		**II**		**III**		**IV**		**V**		
	F	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	
January			49	29	9	84	4	4	108	42	329
February			43	33	4	57		10	61	27	235
March			73	34	3	75	3	20	48	29	285
April		1	88	61	3	42			54	36	285
May		1	123	69	3	61		1	14	16	288
June			61	41	2	43		2	3	15	167
July		5	74	30	4	19		1	12	18	163
August			49	8	16	30	1	3	14	13	134
September	4		90	31	33	60		8	5	9	240
October			35	19	68	48	8	13	4	35	230
November			93	57	102	86	62	20	36	56	512
December			40	16	12	20	13	4	61	16	182
Totals	4	7	818	428	259	625	91	86	420	312	**3050**
	11		**1246**		**884**		**177**		**732**		

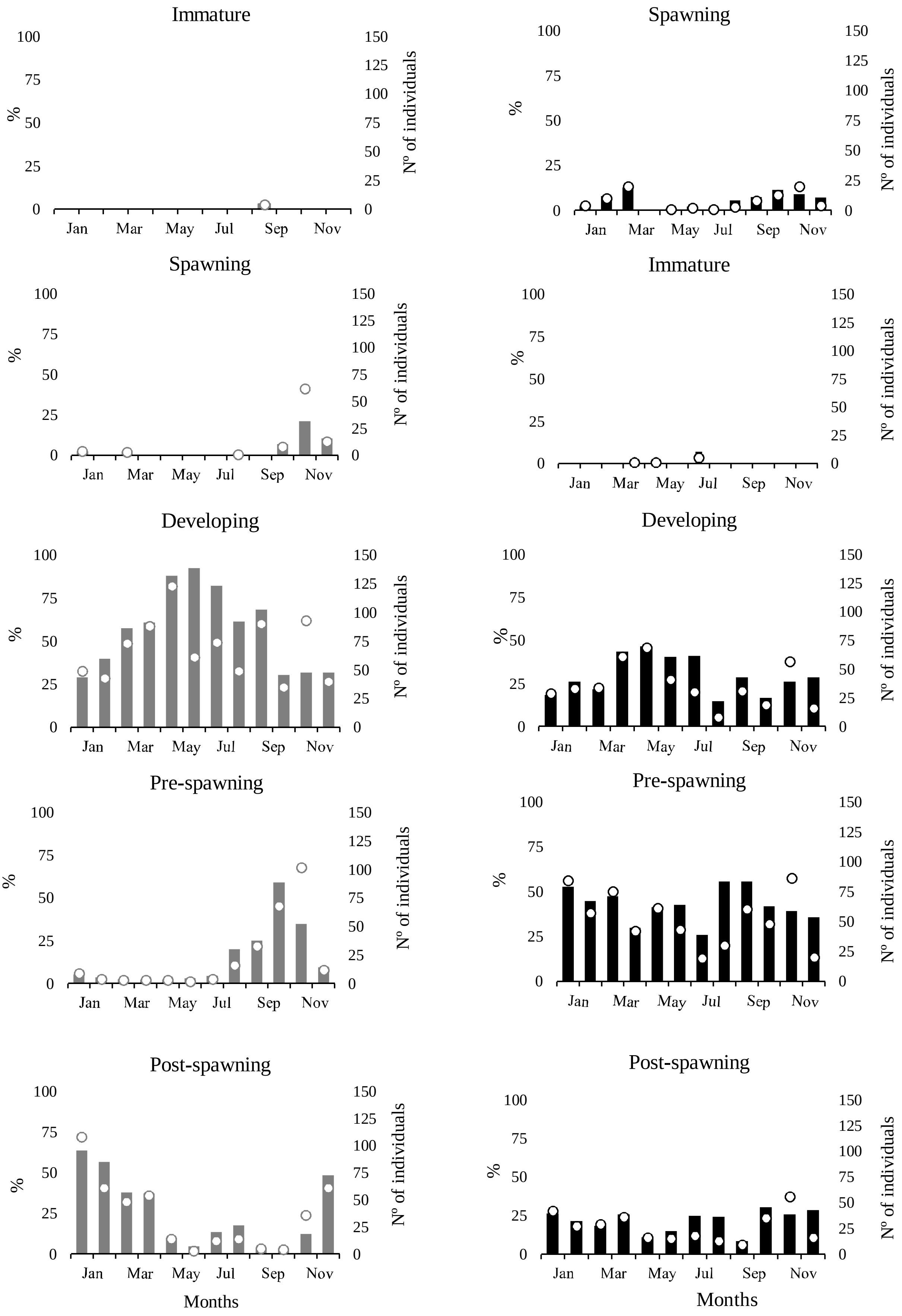


Figure 2.2. Monthly variations of maturity stages for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015.

3.2.2. Sex Ratio

The total sample size analysed was composed of 3106 individuals, 1626 (52.4%) females and 1480 (47.6%) male individuals (*Table 2.3*). The overall sex ratio differed significantly from 1:1 ratio ($\chi^2 = 7.0476$, $df = 1$, $p = 0.007937$), with females outnumbering males (1:0.91).

Monthly-wise, statistical differences were found in sex proportion ($\chi^2 = 51.049$, $df = 11$, $p < 4.05e^{-07}$). Females outnumbered males on January, April, July, August, September, November and December, while males outnumbered in the remaining 5 months of the period in question. April was the month in which an equal proportion was almost achieved (1:0.96). The largest difference in sex proportion was seen in December, with females clearly outnumbering males (1:0.44). The null hypothesis is rejected in June, August, November and December due to $\chi^2 > \chi^2_{0.05;1}$ and it is not rejected in the remaining months.

Table 2.3. Monthly sex ratio of *A. carbo* caught in Madeiran waters from 2010 to 2015.

Month	Females	Males	n	M/F	Sex ratio	χ^2	*Conclusion*
January	170	159	329	0.94	1:0.94	0.37	Accept Ho
February	112	128	240	1.14	1:1.14	1.07	Accept Ho
March	142	161	303	1.13	1:1.13	1.19	Accept Ho
April	146	140	286	0.96	1:0.96	0.13	Accept Ho
May	141	148	289	1.05	1:1.05	0.17	Accept Ho
June	72	108	180	1.50	1:1.50	7.20	Reject Ho*
July	92	73	165	0.79	1:0.79	2.19	Accept Ho
August	80	54	134	0.68	1:0.68	5.04	Reject Ho*
September	132	108	240	0.82	1:0.82	2.40	Accept Ho
October	118	126	244	1.07	1:1.07	0.26	Accept Ho
November	295	219	514	0.74	1:0.74	11.24	Reject Ho*
December	126	56	182	0.44	1:0.44	26.92	Reject Ho*
Total	**1626**	**1480**	**3106**	**0.91**	**1:0.91**	**6.86**	**Reject Ho***

[a]Ho -> 1:1;   *If $\chi^2 > \chi^2_{0.05;1} = 3.84$ with $p < 0.05$

Regarding length (*Table 2.4*), a total of 2900 individuals were sampled, 1522 (52.5%) females and 1378 (47.5%) males. Sex ratio showed a predominance of females in larger length classes, between 115 cm to 145 cm, and males predominate in smaller length classes, between 85 cm and 110 cm. Significant statistical differences were found between length classes ($\chi^2 = 532.33$, $df = 12$, $p < 2.2e^{-16}$). Proportions-wise, a great difference was observed throughout the sample, from 1 female to 6.38 males in 100 cm length class, to 1:0.96 in 115 cm class, 1:0.19

in 125 cm class and 1:0.15 in the 130 cm class. The length interval with the closest 1:1 ratio was the 115 cm length class (1:0.96). Considering the length interval between 100 cm and 135 cm, where the majority of the individuals sampled are found, the null hypothesis is rejected in all lengths ($\chi^2 > \chi^2_{0.05;1}$), except for the 115 cm length class ($\chi^2 < \chi^2_{0.05;1}$), in which it is just about evenly distributed between males and females.

Table 2.4. Sex ratio per length class of *A. carbo* caught in Madeiran waters from 2010 to 2015.

Length (cm)	Females	Males	n	M/F	Sex ratio	χ^2	Conclusion
85	0	1	1	#DIV/0!	1:#DIV/0!	1.00	-------------
90	1	0	1	#DIV/0!	1:#DIV/0!	1.00	-------------
95	0	6	6	#DIV/0!	1:#DIV/0!	6.00	Reject Ho*
100	8	51	59	6.38	1:6.38	31.34	Reject Ho*
105	58	220	278	3,79	1:3.79	94.40	Reject Ho*
110	199	431	630	2,17	1:2.17	85.43	Reject Ho*
115	423	404	827	0,96	1:0.96	0.44	Accept Ho
120	453	197	650	0,43	1:0.43	100.82	Reject Ho*
125	262	50	312	0,19	1:0.19	144.05	Reject Ho*
130	91	14	105	0,15	1:0,15	56.47	Reject Ho*
135	19	3	22	0,16	1:0,16	11.64	Reject Ho*
140	6	1	7	0,17	1:0,17	3.57	Accept Ho
145	2	0	2	0,00	1:#DIV/0!	2.00	-----------
Total	**1522**	**1378**	**2900**	**0.91**	**1:0.91**	**7.15**	**Reject Ho***

*$^{a}H_o$ -> 1:1; *If $\chi^2 > \chi^2_{0.05;1}$ = 3.84 with $p < 0.05$*

3.2.3. Gonadosomatic and Hepatosomatic indexes

The GSI varied significantly in females between months (F = 371.8, df = 1, $p < 2e^{-16}$) throughout the year, ranging from 0.8765 in April to 5.4688 in November (*Figure 2.3*). The first semester of the year exhibits low values, specially between February and May. A distinct increase is noticed from August onwards, peaking in October and November (4.6325 and 5.4688 respectively), an indication that the reproductive activity takes place in the last quarter of the year. In females, GSI values ranged from 1.0447 in April to 2.5086 in August and 2.0655 in September. GSI peaks in August which clear shows that males are reproductively active slightly earlier than females. In males, GSI varied also significantly between months ($F = 81.51$, $df = 1$, $p < 2e^{-16}$).

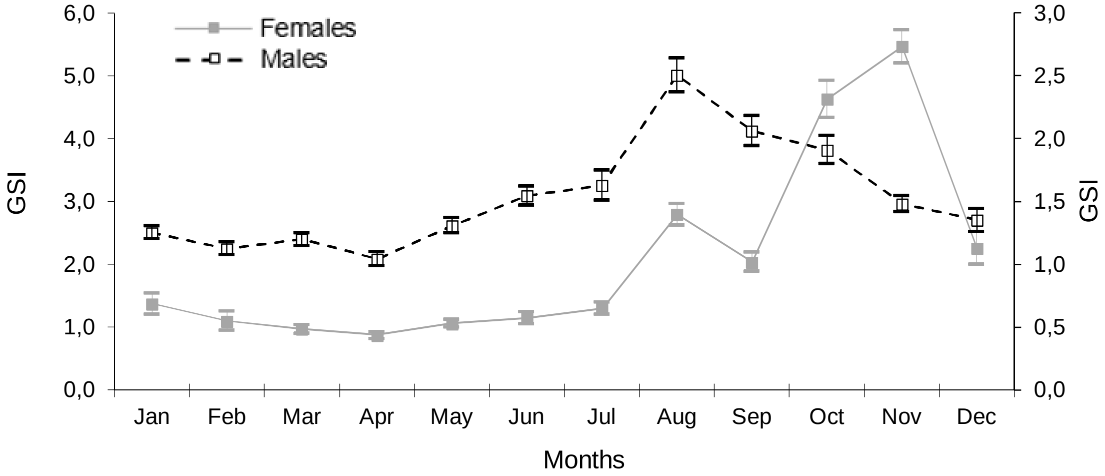


Figure 2.3. Monthly changes in GSI values for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each GSI value is represented by the mean ± SE (error bars).

The GSI varied significantly between maturity stages in females ($F = 752.8$, $df = 5$, $p < 2e^{-16}$) and males ($F = 161.5$, $df = 4$, $p < 2e^{-16}$). GSI mean values ranged from 0.4231 in stage I to 9.9022 in stage IV in females and from 0.9635 in stage II to 2.9144 in stage IV in males (*Figure 2.4*). GSI values were lowest in stage I for females (0.4231) and in stage II for males (0.9635). In contrast, the highest GSI values were found in stage IV for both sexes (9.9022 for females and 2.9144 for males), an indication that ovaries and testis achieve their greatest weight in the spawning stage.

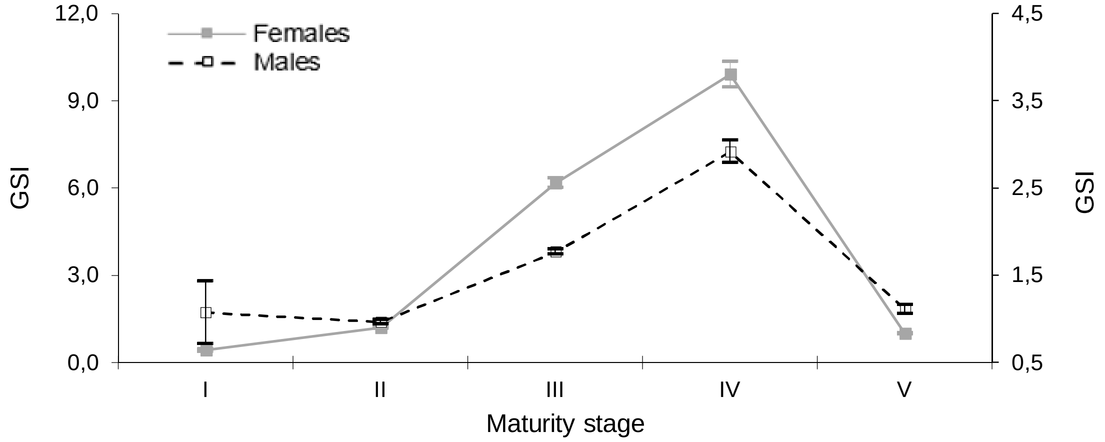


Figure 2.4. Changes in the GSI values in relation with maturity stages for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each GSI value is represented by the mean ± SE (error bars).

In addition, regarding females GSI and total length are highly correlated (r = 0.3636379, $p < 2.2e^{-16}$), varying significantly in females ($F = 121.9$, $df = 1$, $p < 2e^{-16}$) and in males ($F = 40.92$, $df = 1$, $p = 2.17e^{-10}$).

The HSI showed significant differences with regards to months in females ($F = 206.3$, $df = 1$, $p < 2e^{-16}$). It showed the same increasing trend as GSI throughout the year (*Figure 2.5*), ranging from 0.7812 in April to 1.2280 in August. The first semester of the year shows low values, particularly between January and April. June marks the start of a distinct increase, being very noticeable from August onwards. In males, no significant differences were shown in terms of variation of HSI per month ($F = 3.637$, $df = 1$, $p = 0.0567$). HSI values ranged from 0.6637 in February to 0.8022 in August. Considering that males are reproductively active earlier in the year than females, HSI values start to reach their highest values from June onwards till October and November.

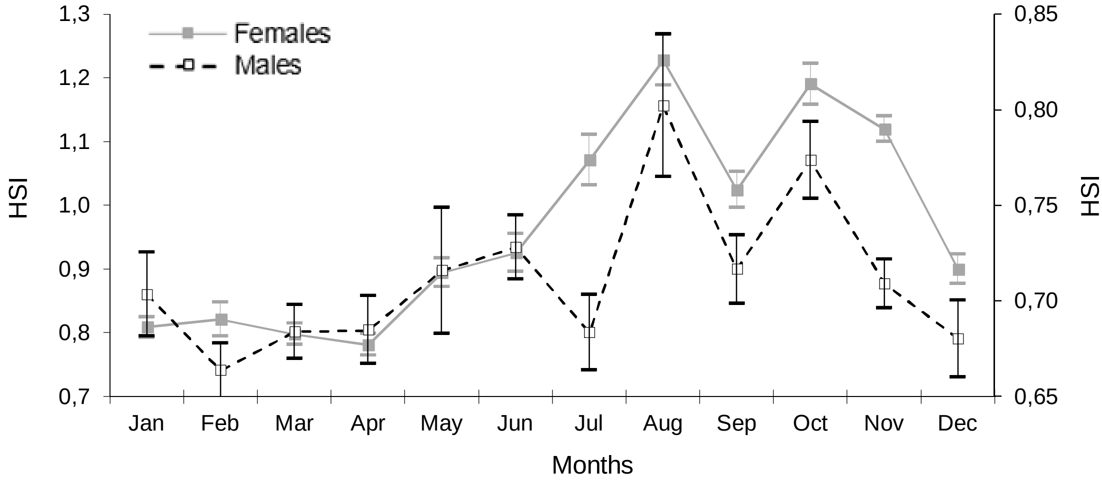


Figure 2.5. Monthly changes in the HSI values for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each HSI value is represented by the mean ± SE (error bars).

Considering the relationship between HSI and maturity stages (*Figure 2.6*), HSI varied significantly in females ($F = 97.56$, $df = 5$, $p < 2e^{-16}$) but not in males ($F = 0.176$, $df = 4$, $p = 0.951$). This may reflect a significant liver function in terms of sexual maturation in females but not as much in males. In females, HSI values by maturity stage varied from 0.6225 in stage I to 1.2889 in stage III. HSI mean values reach their peak slightly before the spawning season. Regarding males, HSI mean values ranged from 0.7046 in stage I to 0.7251 in stage IV. HSI values exhibit a clear increase in stage III, probably related with the increase in body health condition prior to spawning.

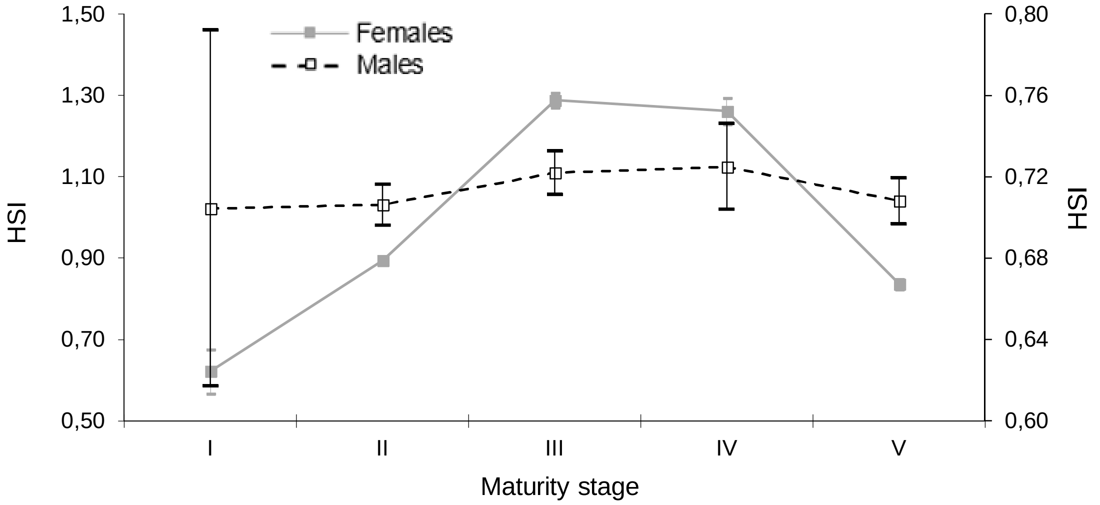


Figure 2.6. Changes in the HSI values in relation with maturity stages for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each HSI value is represented by the mean ± SE (error bars).

The seasonal cycle of the HSI for females is highly related to that of GSI (*rho* = 0.6297061, $p < 2.2e^{-16}$). That of males did not show a significant correlation to GSI (*rho* = 0.04918626, $p = 0.05973$).

When comparing GSI and HSI mean values on a monthly basis, it can be seen that GSI follows the same trend as HSI (*Figure 2.7*). The GSI accompanies the yearly evolution of HSI, in which low values early in the year give rise to a distinct increase before the spawning season. To note that two distinct peaks are clearly visible, one in late August spanning probably to September and another in October and November, which may be related to the different rates that some individuals reach a phase in their sexual development considered optimal for spawning. Similarly, the HSI early in the year has very low values, consistent with lower liver output in terms of gonadal development, starting to increase as the summer approaches, revealing the importance of the liver in the development of the gonads, which is why before and throughout the spawning season it attains its highest values.

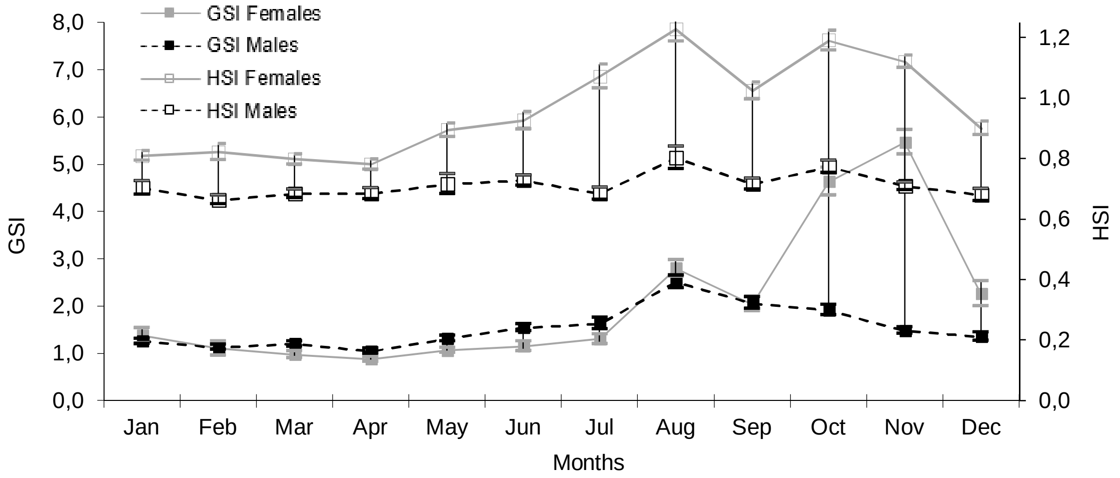


Figure 2.7. Monthly changes in the GSI and HSI values for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each GSI and HSI value is represented by the mean ± SE (error bars).

Similarly, when comparing GSI and HSI mean values per maturity stage, the same pattern arises (*Figure 2.8*). In early stages of gonadal development, the liver has an important role in their development, reaching its highest value in stage III, before starting to decrease as spawning progresses. Moreover, it is much more pronounced in females than in males, considering that no significant differences were found between HSI and maturity stages in males, as was referenced above.

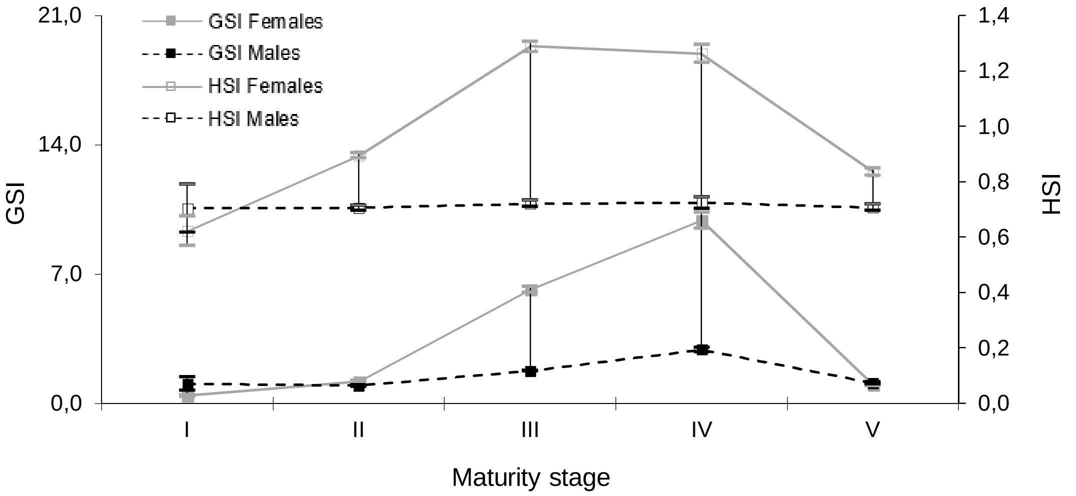


Figure 2.8. Changes in the GSI and HSI values in relation with maturity stages for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each GSI and HSI value is represented by the mean ± SE (error bars).

3.2.4. Length at maturity

The length at first sexual maturity for *A. carbo* was 108.7 cm in females and 102.9 cm in males (*Figure 2.9*), and the determination coefficient was very high in both analysis (0.989 and 0.839 respectively). Furthermore, *Table 2.5* presents a summary of length at first maturity calculated in the present study and by other authors in Madeira. Also, L_{50} estimations from other geographical locations are presented.

Table 2.5. Length at first maturity in the present study and according to other authors regarding several locations throughout the NE Atlantic.

Area	**Length at maturity**		**Author**
	Females	**Males**	
Iceland	92-97 cm	84-88 cm	Magnússon *et al.* (2000)
Hatton Bank	85 cm	91 cm	Anon (1999b)
North Atlantic	80 - 85 cm*		Zilanov & Shepel (1975); Nakamura & Parin (1993)
Madeira	108.7 cm	102.9 cm	Present study
	100.02 - 102.15 cm*		STECF (2014)
	111 cm	101 cm	Santos *et al.* (2013a)
	117.5 cm	97.6 cm	Delgado *et al.* (2013)
	102.8 cm	----------	Bordalo-Machado *et al.* (2001); Figueiredo *et al.* (2003)
Canary Islands	114.4 cm	109.5 cm	Pajuelo *et al.* (2008)
South of NE Atlantic	115 cm	109 cm	Carvalho (2001)

*****These values represent L_{50} estimations for the whole sample, not specifying the sex in the analysis.

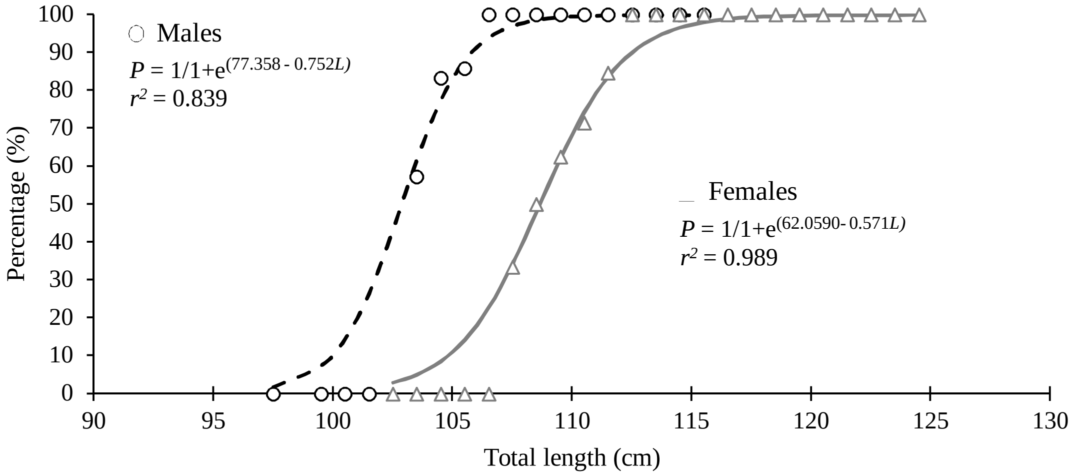


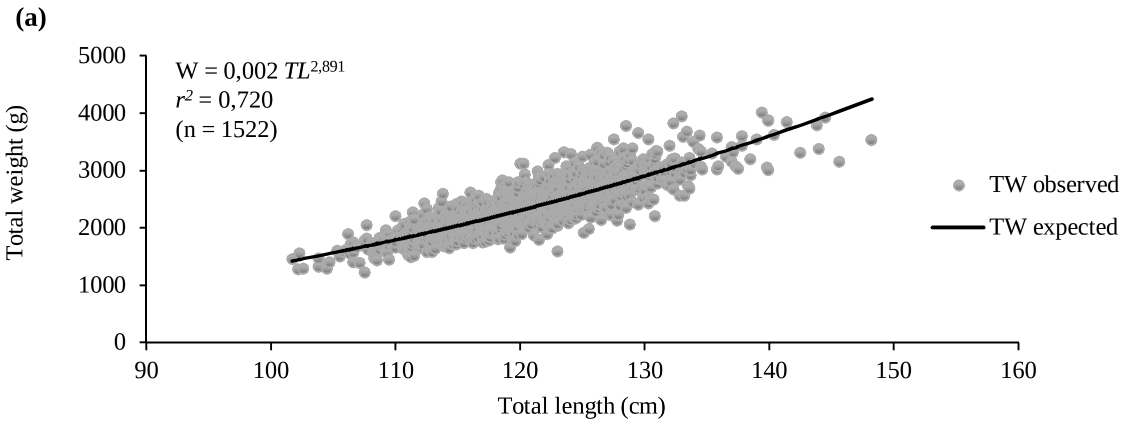
Figure 2.9. Length at first maturity for both sexes of *A. carbo* caught in Madeiran waters from 2010 to 2015.

3.3. Weigh-Length and Length-Length Relationships

The descriptive statistics behind WLRs is presented in *Table 2.6*, and the relationship is presented in *Figure 2.10*. According to the *b*-values, female individuals have a $b = 2.891$, males have a $b = 2.796$ and both sexes have a $b = 2.973$. The coefficient of determination (r^2) is 0.720, 0.733 and 0.774 respectively. All r^2 values are significantly high which indicates that much of the variations in weight is due to variations in length. Females and the both sexes combined exhibit isometric growth ($b = 3$), whereas males exhibit a non-isometric growth ($b < 3$), in this case hypoallometric, confirmed by the *t*-test. Hence, regarding the latter analysis, females and both sexes analysed together exhibit a growth where all dimensions' increase at the same rate, while males exhibit a growth where individuals increase less in weight than predicted by its increase in length, *i.e.*, become more elongated as they grow (Froese *et al.*, 2011). To conclude, for females and both sexes analysed together, the null hypothesis is accepted, confirmed by the *t*-value, which falls within the confidence interval. Conversely, the null hypothesis is rejected for males, confirmed by the *t*-value < -1.96, falling off the 95% confidence interval ($-1.96 < t < -1.96$; Montgomery, 2013).

Table 2.6. Descriptive statistics and WLR parameters for both sexes, separated and combined, of *A. carbo* in Madeiran waters, from 2010 to 2015 [n: sample size; T_L: total length (cm); T_W: total weight (g); WLR equation: $W = aL^b$ (Ricker, 1975); *a*: intercept; *b*: slope of regression model; SE: standard error of *b*; *CI*: confidence interval; r^2: coefficient of determination; *t*-test of *b* for $\alpha = 0.05$: $-1.96 < t < 1.96$].

Sex	*n*	*TL range (cm)*	*TW range (g)*	*WLR equation*	*a*	*b*	*SE of b (95% CI)*	*t-test of b*	r^2	*Relationship type*
Females	1522	101.7 – 148.2	1227.0 – 4025.0	$W = 0.002L^{2.891}$	0.002	2.891	0.096 (2.703 - 3.089)	-1.129	0.720	Isometry
Males	1373	99.0 – 136.1	1157.0 – 3142.0	$W = 0.003L^{2.796}$	0.003	2.796	0.087 (2.626 - 2.965)	-2.364	0.733	Allometry (-)
Total	2895	99.0 – 148.2	1157.0 – 4025.0	$W = 0.002L^{2.973}$	0.002	2.973	0.093 (2.791 - 3.155)	-0.292	0.774	Isometry



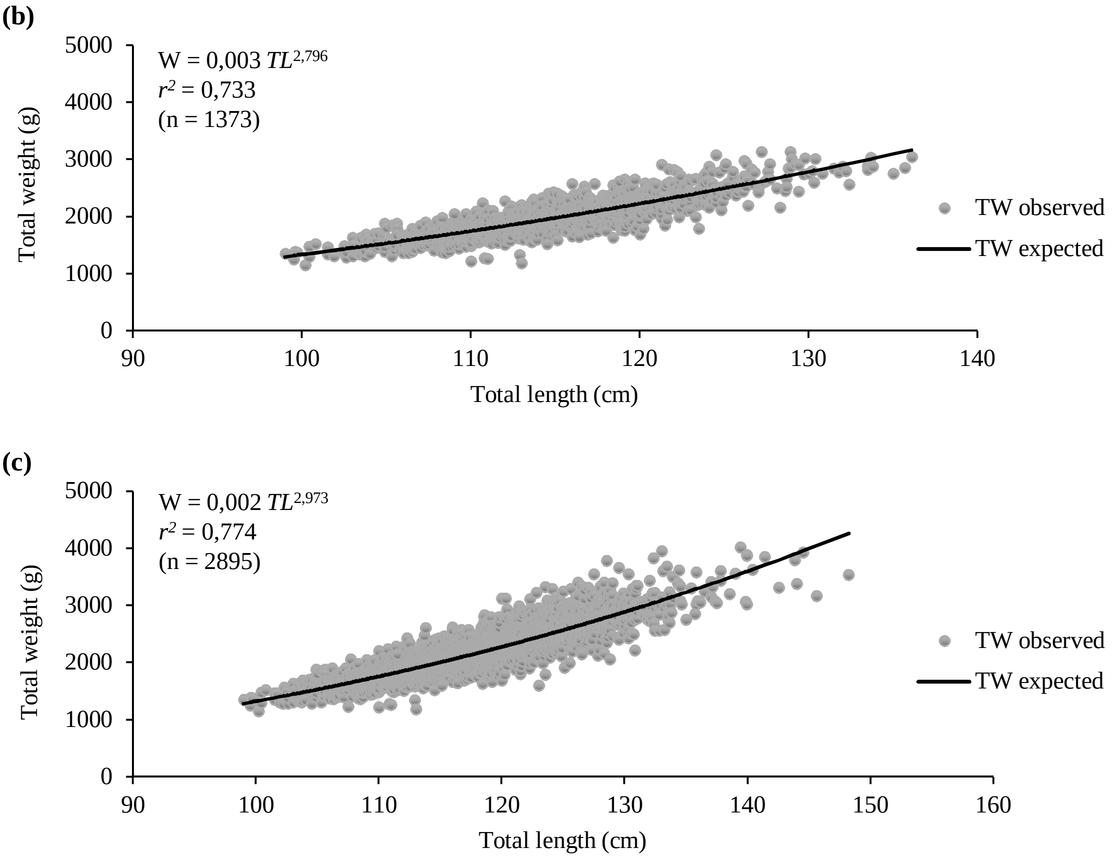
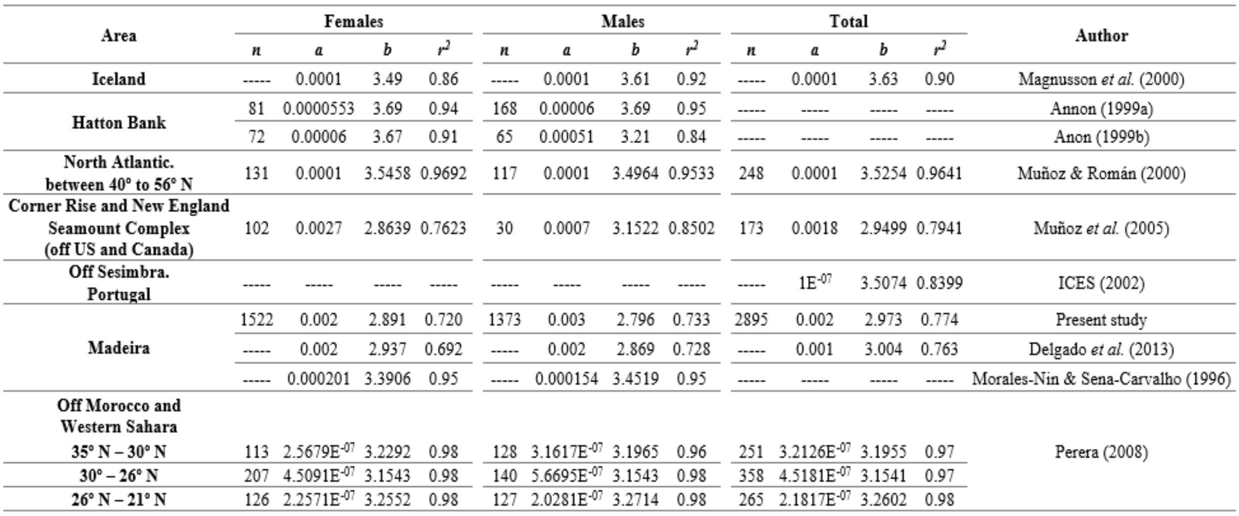


Figure 2.10. WLRs for females (a), males (b) and for both sexes (c) of *A. carbo* caught in Madeiran waters from 2010 to 2015.

Additionally, WLRs from other authors are presented here as a summary in *Table 2.7*. A tendency is clearly shown in which *b*-values tend to decrease with the decrease in latitude or in other words, growth tends to approximate to isometry or being less positively allometric further south.

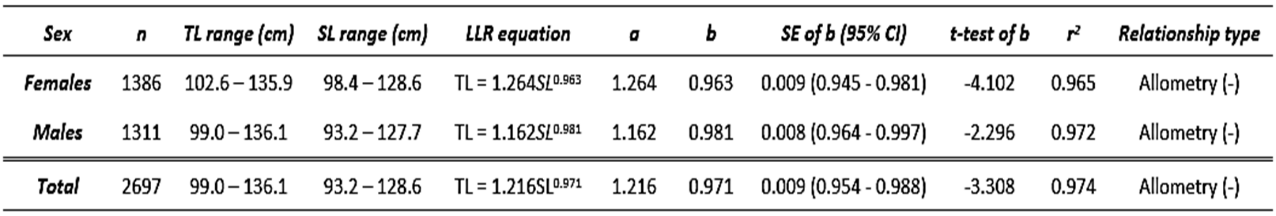
Table 2.7. Descriptive statistics of WLRs in this study and by other authors in different geographical locations throughout the NE Atlantic.



Area	Females				Males				Total				Author
	n	*a*	*b*	r^2	*n*	*a*	*b*	r^2	*n*	*a*	*b*	r^2	
Iceland	-----	0.0001	3.49	0.86	-----	0.0001	3.61	0.92	-----	0.0001	3.63	0.90	Magnusson *et al.* (2000)
Hatton Bank	81	0.0000553	3.69	0.94	168	0.00006	3.69	0.95	-----	-----	-----	-----	Annon (1999a)
	72	0.00006	3.67	0.91	65	0.00051	3.21	0.84	-----	-----	-----	-----	Anon (1999b)
North Atlantic. between 40° to 56° N	131	0.0001	3.5458	0.9692	117	0.0001	3.4964	0.9533	248	0.0001	3.5254	0.9641	Muñoz & Román (2000)
Corner Rise and New England Seamount Complex (off US and Canada)	102	0.0027	2.8639	0.7623	30	0.0007	3.1522	0.8502	173	0.0018	2.9499	0.7941	Muñoz *et al.* (2005)
Off Sesimbra. Portugal	-----	-----	-----	-----	-----	-----	-----	-----	-----	$1E^{-07}$	3.5074	0.8399	ICES (2002)
Madeira	1522	0.002	2.891	0.720	1373	0.003	2.796	0.733	2895	0.002	2.973	0.774	Present study
	-----	0.002	2.937	0.692	-----	0.002	2.869	0.728	-----	0.001	3.004	0.763	Delgado *et al.* (2013)
	-----	0.000201	3.3906	0.95	-----	0.000154	3.4519	0.95	-----	-----	-----	-----	Morales-Nin & Sena-Carvalho (1996)
Off Morocco and Western Sahara													
35° N – 30° N	113	$2.5679E^{-07}$	3.2292	0.98	128	$3.1617E^{-07}$	3.1965	0.96	251	$3.2126E^{-07}$	3.1955	0.97	Perera (2008)
30° – 26° N	207	$4.5091E^{-07}$	3.1543	0.98	140	$5.6695E^{-07}$	3.1543	0.98	358	$4.5181E^{-07}$	3.1541	0.97	
26° N – 21° N	126	$2.2571E^{-07}$	3.2552	0.98	127	$2.0281E^{-07}$	3.2714	0.98	265	$2.1817E^{-07}$	3.2602	0.98	

The description on LLRs characteristics is shown in *Table 2.8*. Slope-values (*b*) and r^2 have mean values of 0.972 and 0.970 respectively. Both variables are correlated, as expected, being confirmed by the Pearson's correlation test, in which a positive correlation was obtained resulting in the interpretation that total length is correlated with standard length (*cor* = 0.2478769, $p < 2.2e^{-16}$). Because *t*-values falls off the interval established by the critical values from the *t*-distribution table (Montgomery, 2013), the null hypothesis must be rejected, hence indicating hypoallometric growth between TL and SL ($p < 0.05$). Since mean value of *b* for LLR was significantly lesser than 1 ($b < 1$), as expected by isometric growth, increment in TL is more per unit increment than SL. Therefore, as the only difference in TL and SL is the length of the caudal fin, it can be deduced that by increasing in total length, the caudal fin does not increase proportionally but grows with lesser increments.

Table 2.8. Descriptive statistics and LLR parameters for both sexes of *A. carbo* in Madeiran waters, from 2010 to 2015 [n: sample size; T_L: total length (cm); S_L: standard length (cm); LLR equation: $T_L = aS_L^b$ (Ali *et al.*, 2013; Keskar *et al.*, 2015); *a*: intercept; *b*: slope of regression model; *SE*: standard error of *b*; *CI*: confidence interval; r^2: coefficient of determination; *t*-test of *b* for $\alpha = 0.05$: $-1.96 < t < 1.96$].



Sex	*n*	*TL range (cm)*	*SL range (cm)*	*LLR equation*	*a*	*b*	*SE of b (95% CI)*	*t-test of b*	r^2	*Relationship type*
Females	1386	102.6 – 135.9	98.4 – 128.6	$TL = 1.264SL^{0.963}$	1.264	0.963	0.009 (0.945 - 0.981)	-4.102	0.965	Allometry (-)
Males	1311	99.0 – 136.1	93.2 – 127.7	$TL = 1.162SL^{0.981}$	1.162	0.981	0.008 (0.964 - 0.997)	-2.296	0.972	Allometry (-)
Total	2697	99.0 – 136.1	93.2 – 128.6	$TL = 1.216SL^{0.971}$	1.216	0.971	0.009 (0.954 - 0.988)	-3.308	0.974	Allometry (-)

3.4. Condition factor

K_{rel} showed statistical differences between maturity stages in females ($F = 47.85$, $df = 5$, $p < 2e^{-16}$) and males ($F = 13.56$, $df = 4$, $p = 7.64e^{-11}$), but not regarding total length in females ($F = 0.241$, $df = 1$, $p = 0.623$) and in males ($F = 0.082$, $df = 1$, $p = 0.774$). K_{rel} also showed significant differences on a monthly basis in females ($F = 80.3$, $df = 1$, $p < 2e^{-16}$), but regarding males, K_{rel} did not show statistical differences by month ($F = 1.06$, $df = 1$, $p = 0.303$). The fact in males K_{rel} does not vary significantly monthly and with different length classes may have to do with a much more pronounced role that liver function has in the development of ovaries rather than in testis development. This detail may be due to the fat that reproduction is costlier to females than it is to males, hence varying quite greatly in the sex carrying the burden of generating new offspring.

K_{rel} exhibits low values between March and June for females and between March and May for males and exhibits high values between July and November for females and in August, September and November for males (*Figure 2.11*). K_{rel} in females rises from its lowest figure in March and April (0.219) to its highest in November (0.234), although reaches high values in July, before the spawning season. Regarding males, K_{rel} ranges from its lowest mean value in March (0.339) to its highest value in August (0.355). The highest K_{rel} values are registered in the spawning period, between September and November, although in males, K_{rel} peaks earlier, probably in light of the fact that males enter the spawning season earlier than females.

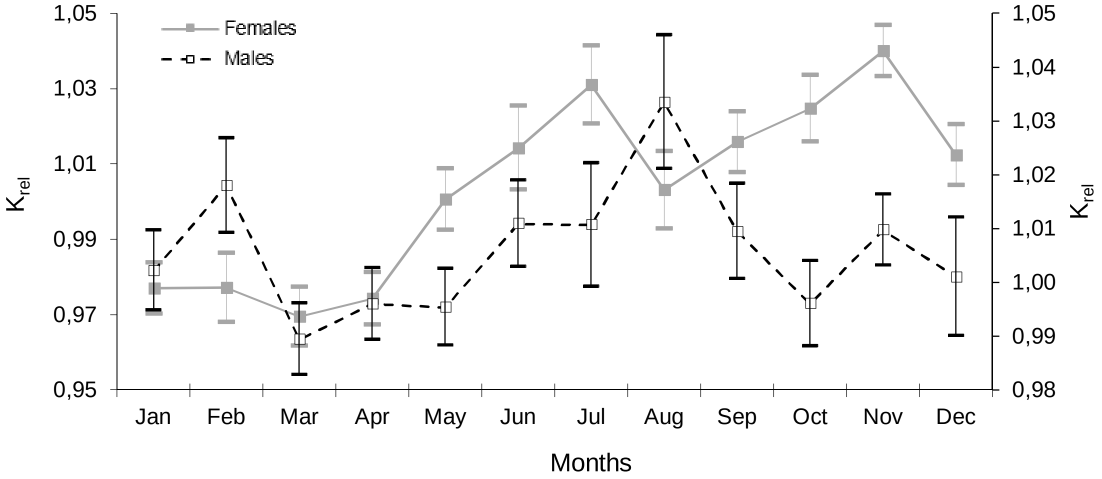


Figure 2.11. Monthly changes in the K_{rel} values for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each K_{rel} value is represented by the mean ± SE (error bars).

Considering the relationship with maturity stages (*Figure 2.12*), K_{rel} ranges from 0.202 in stage I to 0.250 in stage IV in females and in males it ranges from 0.327 in stage I to 0.365 in stage IV. Thus, K_{rel} follows the same trend as GSI and HSI in regards to maturity stages. It peaks in stage IV for both sexes alongside GSI and HSI, indicating that the increased robustness (or ‘well-being’) of the fish is followed by an increase in gonad and liver proportion to body weight, revealing a greater feeding activity towards the latter stages of sexual development.

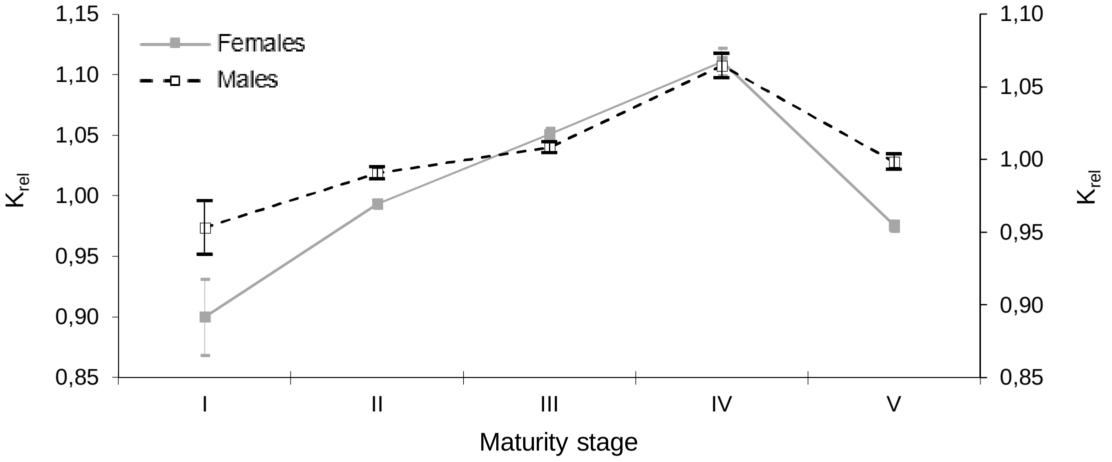
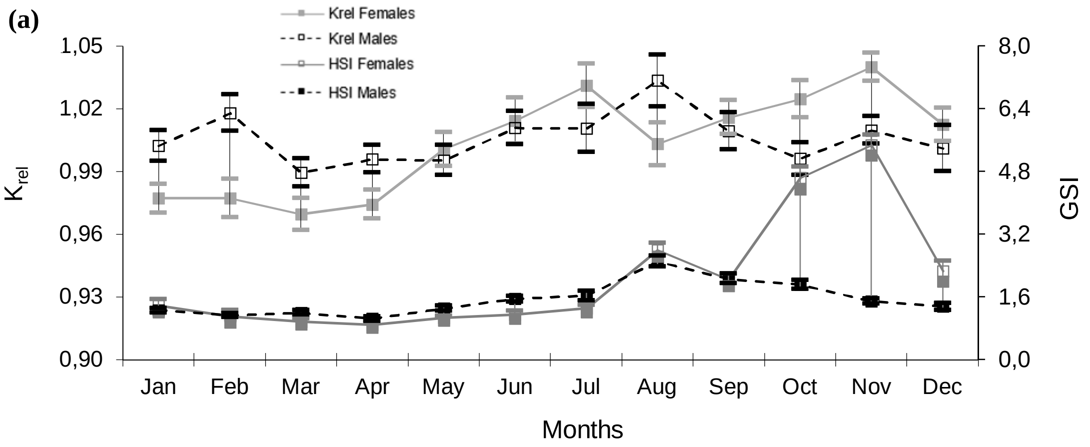


Figure 2.12. Changes in K_{rel} values in relation with maturity stages for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each K_{rel} value is represented by the mean ± SE (error bars).

K_{rel} is highly correlated with GSI in females (*cor* = 0.3094937, $p < 2e^{-16}$). Concerning males, a correlation exists but not as strong (*cor* = 0.2204987, $p < 2e^{-16}$). Similarly, a correlation exists between K_{rel} and HSI in females (*cor* = 0.4133533, $p < 2e^{-16}$) and in males (*cor* = 0.1861121, $p = 1.952e^{-08}$), showing clearly that a healthy body condition is highly related to the spawning event.

An increase in K_{rel} is followed by an increase in GSI, consistent with the fact that prior to the spawning season, the finest body condition is attained (*Figure 2.13a*). This is also visible when plotting K_{rel} with GSI per maturity stages (*Figure 2.13b*), in which both variables have similar behaviours, reaching their maxima in stage IV, by the time spawning occurs.



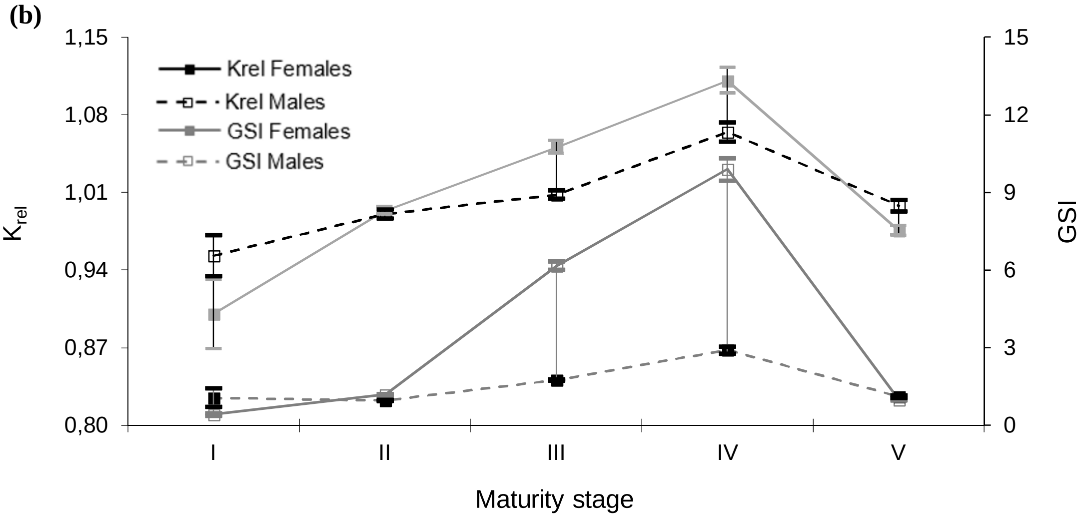
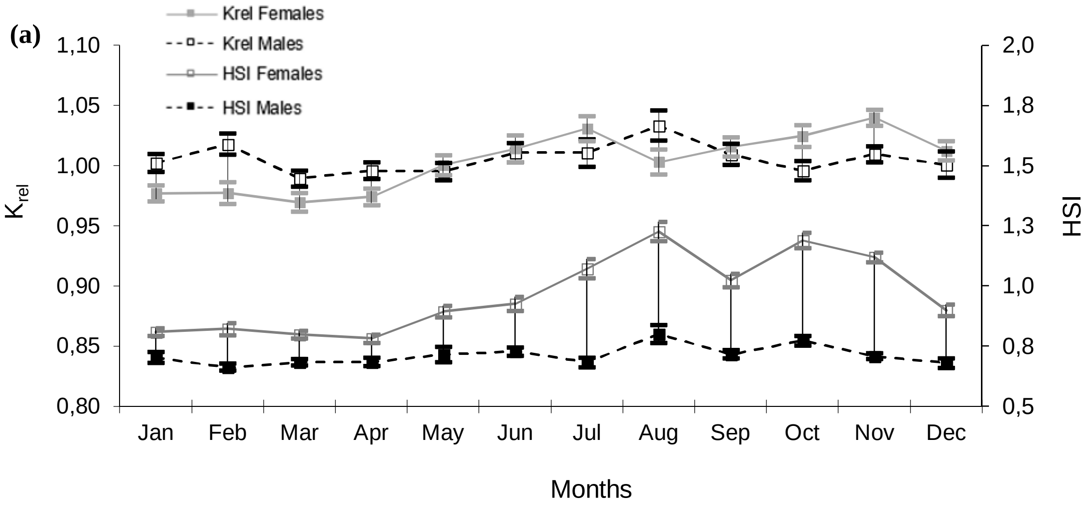


Figure 2.13. Monthly changes (a) and per maturity stage (b) in K_{rel} and GSI values for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each K_{rel} and GSI value is represented by the mean ± SE (error bars).

Considering the relationship between K_{rel} and HSI, related pathways can be observed, in which body condition and the liver increase their volume as the year progresses towards the spawning season (*Figure 2.14a*). A similar path is seen regarding maturity stages (*Figure 2.14b*).



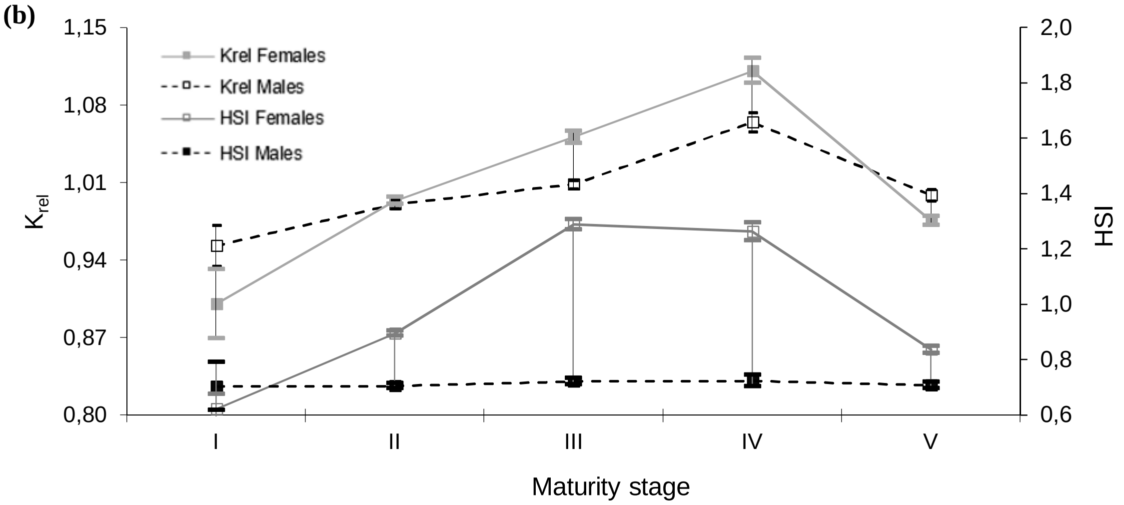


Figure 2.14. Monthly changes (a) and per maturity stage (b) in K_{rel} and HSI values for females and males of *A. carbo* caught in Madeiran waters from 2010 to 2015. Each K_{rel} and HSI value is represented by the mean ± SE (error bars).

4. Discussion

Understanding the population dynamics of a heavily exploited marine resource such as *A. carbo*, implies the application of continuous efforts by the fishing industry and researchers to increase the knowledge concerning this species. These initiatives are paramount, and evenly more so considering that deep-water species are generally long-lived, slow-growing, mature late and have low fecundity, particularities that epipelagic species do not share entirely (Morato *et al.,* 2006; Norse *et al.,* 2012). Although *A. carbo* may somewhat differ from these observations (*i.e.* fast growth rate for a deep-sea fish, maturing at about 3 to 4 years and with longevity of 12–24 years) (Morales-Nin & Sena-Carvalho, 1996; Morales-Nin *et al.,* 2002; Figueiredo *et al.,* 2003; Vieira *et al.,* 2009; Norse *et al.,* 2012), the ecological characteristics of these species make them vulnerable to over-exploitation, conferring them a status of slow recovering units (Morato *et al.,* 2006), much more sensitive to intensive commercial exploration than their epipelagic counterparts, hence monitoring programs must be kept to maintain this resource within healthy numbers.

This study encompassed several key biological features, fundamental in understanding the idiosyncrasies of the species in Madeiran waters. Biological traits of fish are remarkably plastic and change in response to regional fishing intensity, environmental conditions and other local phenomena (Pajuelo *et al.*, 2008). Although questions still exist regarding the life cycle of black scabbardfish, the most widespread hypothesis is that this species reveals one single stock, which undertakes a large-scale clockwise migration, between northern and southern latitudes in NE Atlantic (Gordo *et al.,* 2009; Farias *et al.,* 2013). Therefore, an increase in knowledge in terms of the biology of black scabbardfish is important for managing concerns across nations in this part of the Atlantic, although a complete study covering all regions from its distribution is still to be made.

The results attained showed clear differences between both sexes in length- and weight-frequency distributions. Females were the largest and heaviest specimens while males were the smallest and lightest ones, coinciding with previous studies of Morales-Nin & Sena-Carvalho (1996), Figueiredo *et al.* (2003), Pajuelo *et al.* (2008), Delgado *et al.* (2013) and Santos *et al.* (2013a). Also, analysing length-frequencies of individuals caught in northern latitudes from other studies, specimens caught off Madeira exhibited greater length than their counterparts caught in northern latitudes, such as off mainland Portugal, Spain, France, west of the British Isles and in Icelandic waters (Bordalo-Machado *et al.,* 2001; Santos *et al.,* 2013a). This particularity is related with two intrinsic details: 1) spawning occurs only in the southern areas of its distribution, namely in Madeira and Canary Islands; 2) black scabbardfish artisanal fishery off Madeira exploits only larger fish and thus mature individuals, being highly selective in that regard (due to gear design specifics; Bordalo-Machado & Figueiredo, 2009). Hence, although this study did not deal with smaller individuals, the fact that the majority of the sample is composed of larger individuals, when comparing with studies which focused on northern latitudes (*e.g.* Bordalo-Machado *et al.,* 2001; Figueiredo *et al.,* 2003), is a proof that size segregation exists between northern and southern latitudes, being very likely that this difference may be related to life cycle specifics and migration patterns (Santos *et al.*, 2013a).

The macroscopic assignment of maturity stages was performed following the indications provided by Gordo *et al.* (2000). All maturity stages were observed. As expected, immature individuals were the least common, and mature were the commonest ones. Individuals that are sexually mature, but are not reproducing represent a part of the population where spawning will simply not occur or has effectively occurred. The fact that mature individuals in developing stage (II) consist the majority of the sampled population (40%) may be related with energetic costs of migration. Once a certain size is reached, most of the energy is allocated to reproduction matters (Santos *et al.,* 2013a), thus remaining in Madeiran waters whether to achieve that purpose, especially those larger individuals that undertake spawning in January and February as stated by Figueiredo *et al.* (2003), or to effectively feed, increasing their body condition before moving northward (Neves *et al.*, 2009). Moreover, it is usually assumed that iteroparous teleost fishes spawn annually when they reach sexual maturity. Since the greater part of the sample is composed of individuals in stage II, *i.e.*, developing/recovering stage, it may be right to assume that perhaps some of those individuals, although sexually mature, do not spawn.

According to a study done by Jørgensen *et al.* (2006), an extensive and energy-costly migration makes skipped spawning an attractive option. Since skipping that event results in energy savings, this possibly leads to a large increase in future fecundity. It seems that black scabbardfish goes through an intense feeding activity on blue whiting (*Micromesistius poutassou*), between January and April (Santos *et al.,* 2013b), and the fish with better nutritional conditions migrate southwards to progress with maturation and spawning. Hence, as pointed out by Neves *et al.* (2009), the presence of non-reproductive individuals in Madeiran waters may indicate the occurrence of skipped spawning, though confirmation merits further investigation.

In addition, as mentioned earlier and in accordance with previous studies (*e.g.* Pajuelo *et al.*, 2008; Neves *et al.*, 2009; Santos *et al.*, 2013a), the possible explanations for the low number of immature specimens could be that they are not being selected by the longline fishing gear due to design specifics (Bordalo-Machado & Figueiredo, 2009, or they have a different vertical distribution or as Bordalo-Machado *et al.* (2001), Figueiredo *et al.* (2003), Delgado *et al.* (2013), Santos *et al.* (2013a) and STECF (2014) state, very few immature individuals are present in Madeiran waters.

In fish, sex ratio varies considerably from species to species, although the majority of species is close to 1:1 ratio. It may differ from one population to another of the same species and may vary seasonally and yearly in the same population (Palazón-Fernández *et al.*, 2001). In this study, the overall sex ratio differed from 1:1 ratio ($p < 0.05$). Overall, males were outnumbered by females. Monthly-wise, differences were found in sex proportion. Female numbers were higher than those of males in the spawning season, defined here as the period from September to December, in accordance with previous authors (Figueiredo *et al.*, 2003; Pajuelo *et al.*, 2008; Neves *et al.*, 2009; Farias *et al.*, 2013; Santos *et al.*, 2013a). Also, females outnumbered males in January, April and during the summer months, prior to the spawning season.

Size related differences in sex ratios were as well observed. Significant deviations from 1:1 ratio were observed among the extreme length classes, including 105 cm length class and below, and in 125 cm length class and above. Females predominated the largest sizes while the smallest classes were disproportionately male. These differences observed in size-specific sex ratio of black scabbardfish have also been reported by other authors (*e.g.* Pajuelo *et al.*, 2008; Delgado *et al.* 2013) and are in accordance with observations done in previous analysis regarding the population structure, in which males are the smallest individuals and females attain greater lengths than the opposite sex.

Previous studies have demonstrated that the black scabbardfish carries out its sexual cycle throughout the NE Atlantic. Immature and non-reproductive specimens predominate off mainland Portugal, France and the British Isles, while mature specimens are found in the Macaronesian waters of Madeira and Canary Islands archipelagos (Neves *et al.*, 2009; Delgado *et al.*, 2013; Santos *et al.*, 2013a; Santos *et al.*, 2013b).

In this study the spawning season is clearly distinguishable. The GSI monthly progression indicates that the spawning season starts around September and finishes in December, with a peak in November, which is in agreement with previous conclusions (*e.g.* Bordalo-Machado *et al.*, 2001; Figueiredo *et al.*, 2003; Neves *et al.*, 2009; Delgado *et al.*, 2013;

Santos *et al.*, 2013a). It can be seen that the spawning season differs between sexes. Males reach sexual maturity earlier in the year than females, around August, which is confirmed by the GSI values that peak in the aforementioned month. Females attain sexual maturity from October onwards. Also, both sexes attain ripening condition at stage IV, followed by a clear sharp decrease in gonad size in stage V. Thus, GSI constituted an important tool in the attribution of maturity stages and in the definition of the spawning period since GSI does not overlap from one stage to another (Figueiredo *et al.,* 2003).

The liver accumulates energetic reserves and since it is important in terms of metabolic activity, it is used as a proxy for attaining gonad ripe condition for it decreases in terms of volume, as energy is redeployed into gonad maturation prior to or during spawning season (Dorcas & Solomon, 2014). Accordingly, a decrease in monthly HSI mean values was observed during the spawning season. It attained the highest mean values in August in both sexes, prior to the spawning season only to decrease continually throughout the spawning period, though with a significant increase in October. These results differed slightly from those presented by Santos *et al.* (2013a), since in that study HSI peaked in October for both sexes. This may indicate that prior to spawning, the increase in feeding activity results in greater energetic reserves and metabolic activity from the liver, which in turn allocates to oogenesis and spermatogenesis during the spawning season.

The hepatosomatic index increased gradually with increased sexual maturation. It attained greater mean values in stage III in females and in stage IV in males. A significant correlation was observed between GSI and HSI for females. This comes in light of previously stated arguments, where the major events responsible for the development of oocytes involve the storage and conversion of a hepatically derived plasma precursor, vitellogenin, into yolk protein, suggesting that liver reserves amass prior to reproduction, hence attributing the liver a key part in the gradual sexual maturation process in fishes (Palazón-Fernández *et al.*, 2001; Neves *et al.*, 2009).

In association with the GSI and HSI, the condition factor (K_{rel}) reflects through its variations, information on the physiological state of the fish in relation to its ‘well-being’ (Le Cren, 1951). Generally, it is characterized by a decrease in periods of low temperatures and/or shortage of food, an increase towards the spawning season followed by a steep decline after spawning, particularly in females (Froese, 2006). Thus, it is key in understanding the aggregation of body condition with sexual maturation processes.

In this study and regarding females, K_{rel} varied significantly throughout the year. Since females attain a reproductively active role later in the year than males, body condition mean values were highest in the spawning season, from September to November, peaking in the last. In males, K_{rel} varied slightly differently. K_{rel} started to increase in the beginning of the summer in June, peaking in August, before the spawning season, following the same pattern exhibited by GSI and HSI, decreasing after the spawning season. Since males attain a reproductively active role earlier in the year than females, it is expected that K_{rel} is highest in accordance with that fact.

Furthermore, K_{rel} amassed in stage IV in both sexes, since it is the stage where individuals are actively spawning. K_{rel} was significantly correlated with GSI and HSI in both sexes, as expected since they reflect the increase in gonad and liver weight proportion to body weight and overall body condition as the year progresses and ripe condition is attained. To conclude, as phrased by Santos *et al.* (2013a), individuals in which a given body condition does not allow them to reproduce in a certain year, skipping this event is an efficiently important approach for saving energy that can then be allocated to growth and large scale migration, as well as to subsequent reproduction in the following year.

Even though gonad development and subsequent spawning may be contingent on several environmental stimuli, individuals must attain a certain size or age before they can reproduce (King, 1995). Length at maturity is obtained by separating adults from juveniles and constituting proportions, in order to reach an accurate L_{50} estimation.

The length at sexual maturity was estimated for both sexes, covering only the spawning season, as postulated by Bordalo-Machado *et al.* (2001) and Figueiredo *et al.* (2003). In this study, and in comparison terms, L_{50} for females is higher than what was published by Figueiredo *et al.* (2003), Bordalo-Machado *et al.* (2001) but lower than what was published by Delgado *et al.* (2013) and Santos *et al.* (2013a), all of which examples from studies conducted in Madeiran waters. Regarding males, L_{50} is higher than what was published by Delgado *et al.* (2013) and by Santos *et al.* (2013a). If comparison is made with estimations done with specimens from northern and southern latitudes, L_{50} from this study is higher comparing with specimens from northern latitudes and lower for specimens from southern latitudes for both sexes respectively. Pajuelo *et al.* (2008) and Santos *et al.* (2013a) postulated that this difference could be explained mainly by a very low number of immatures in the present study, since mostly matures are found in Madeiran waters, by the time of sampling, and also could be related to differences in regional oceanographic conditions or their level of exploitation. Additionally, an intrinsic detail in terms of black scabbardfish biological studies is related to the nature in which studies were conducted. Considering that prior to 2010 *A. carbo* wasn't being distinguished from *A. intermedius*, distorts to some extent, any conclusion from studies prior to that year.

The length and weight of a fish are intrinsically connected. These variables allow to increase the knowledge on the structure of the population, reproduction history, growth patterns and are very useful in local and interregional morphological and life comparisons among species and populations. Also, they constitute a key tool in assessing a fishes' 'well-being' or physiological status (Froese, 2006).

Regarding WLRs, in this study females exhibited isometric growth while males exhibited negative allometric growth. Both sexes combined also exhibited isometric growth. These results come in light of previously estimated WLR parameters in Delgado *et al.* (2013) for Madeiran waters. Since prior to 2010 *A. carbo* wasn't being distinguished from *A. intermedius*, results from papers prior to that date are somewhat biased and extrapolation may be unreliable. Also, as WLR parameters yield variability, differing between seasons, years and many other factors, namely food availability, feeding rate, gonad development and spawning season, direct comparison with studies from other latitudes, like the ones from Hatton Bank or Iceland may be unreasonable (Froese, 2006).

Consequently, in a biological point of view, females exhibited a proportionality between length and weight increase ($b = 3$) while males showed an increase in body length disproportional to increase in weight ($b < 3$). In other words, regarding females, specimens increase in weight as much as in length. Conversely, regarding males, increase in weight is lower than increase in length, hence specimens have changed their body shape to become more elongated (Froese, 2006).

Strong allometric growth patterns are rare and a discussion of the potential benefits associated with such ontogenetic change in body proportions ought to be made (Froese, 2006). Comparing these findings to studies conducted in other latitudes, *b*-values are much lower in this study. Although direct comparison may not be correct, from a physiological point of view, it makes sense specimens from Madeira exhibit negative allometric growth, such as the case of males. Reproduction is a costly endeavour, and since mature individuals come to southern latitudes to reproduce, it is expected that growth shifts from one of building reserves and preparing for a large scale migration, increasing more in weight than in length, to a type of growth that favours reproductive success, in which gonad development is promoted over somatic growth (Froese, 2006).

In addition, *A. carbo* with its elongated body and large mouth makes it clear it is a top benthopelagic predator (Santos *et al.*, 2013b). Since it has to hunt for its prey, namely blue whiting, especially in northern areas of its distribution (*Micromesistius poutassou*), cephalopods (*Chiroteuthis* spp., *Mastigoteuthis* sp., *Taonius* sp.) and fish (Myctophidae and

Chauliodus spp.) (Farias *et al.*, 2013), elusive as its prey can be such as squids, having an elongated body can be an advantage by favouring swimming speed when chasing such a prey in the water column.

Due to the fishing gear selectivity and the fact Madeiran waters are a spawning ground for black scabbardfish, the sample did not include juveniles or very small individuals. As stated by Petrakis & Stergiou (1995), WLRs ought to be limited to the size ranges applied in the estimation of the parameters' regression. Therefore, extrapolation to larvae, immatures or juveniles may be incorrect.

Alongside WLRs, LLRs of fish can also be very useful on providing information on growth patterns and ecology (Ali *et al.*, 2013; Keskar *et al.*, 2015), being able to be used as a management tool for comparative growth studies (Petrakis & Stergiou, 1995; Moutopoulos & Stergiou, 2002; Hossain *et al.*, 2006). The relationship between TL and SL was analysed and a significant correlation was obtained. As expected, total length is positively correlated with standard length, or in other words, the length from the tip of the head to the tip of the caudal fin is correlated with the length from the base of the caudal fin to its tip.

The interpretation of the results attained here are in agreement of a negatively allometric growth pattern between total length and standard length ($b < 1$), coming to the conclusion that the caudal fin grows at different rates (lesser) than the total length. This may be related with the condition upon which individuals are caught and handled. Though no certainties are warranted, many caudal fins come completely destroyed or damaged, so a bias may well be present in the overall estimation of this parameter.

Previous information regarding LLRs for black scabbardfish does not exist, hence comparisons between the results obtained here and other works were not done. Since *A. carbo* and other *Aphanopus spp.* species have an elongated body structure, ecological studies that can investigate the effect of shape on the non-isometric nature of LLRs could shed more light on this issue.

Although it is difficult to exclude all the factors disturbing b-values from WLR and LLR (*e.g.* seasonality, fish feeding, number of fish examined, anthropogenic stressors, sexual maturity, length ranges of the specimens examined, among others), the recommendations given by Froese (2006) were followed wherever possible.

All things considered, the fact remains that all life stages of black scabbardfish are not known. The current understanding of the population dynamics, including early life stages such as larvae and juveniles, in the NE Atlantic imply further studies to narrow the gap between empirical knowledge and assumptions. Over the past six years, since *A. carbo* started to be separated from *A. intermedius* in biological studies, the continued publication of papers and thesis have started to amount, renewing the previously assumed knowledge about this species. As done before, this study comes in that sense, as another tool among many others, to provide an insight of this important marine resource.

CHAPTER 3

Standardization of commercial LPUE data of *Aphanopus spp.* landed in Madeira Archipelago, Portugal

1. Introduction

‘*I believe then that the cod fishery, the herring fishery, pilchard fishery, the mackerel fishery, and probably all the great sea fisheries are inexhaustible: that is to say that nothing we do seriously affects the numbers of fish. And any attempt to regulate these fisheries seems consequently from the nature of the case to be useless*’ (T. H. Huxley, 1883 in King, 1995).

The words of T. H. Huxley in his speech at the London Fisheries Exhibition in 1883 may yield some twisted eyebrows in fishers and fisheries managers of today. In Huxley’s epoch, fishing vessels still used sails, no large international fishing fleets existed, and the world population was much less, about a third of what it is today. Perhaps Huxley could have heeded the words of Thomas Malthus who, over 50 years before in his world famous work entitled ‘*An Essay on the Principle of Population*’, had contended that the world’s population was increasing faster than its means of subsistence (King, 1995). As Malthus wrote:

‘*If the subsistence for man that the earth affords was to be increased every twenty-five years by a quantity equal to what the whole world at present produces, this would allow the power of production in the earth to be absolutely unlimited, and its ratio of increase much greater than we can conceive that any possible exertions of mankind could make it....yet still the power of population being a power of a superior order, the increase of the human species can only be kept commensurate to the increase of the means of subsistence by the constant operation of the strong law of necessity acting as a check upon the greater power*’ (Malthus, 1798).

Although predicted by Thomas Malthus that the human population would increase geometrically, doubling every 25 years despite the arithmetic nature of food production, Huxley’s statement based on the assumed productivity of the oceans, which cover over 70 per cent of the world’s surface and the lack of hunting and farming abilities that humans had (before industrial farming and international industrial fishing vessels), may have not appeared over-optimistic to an audience in 1883 (King, 1995).

As time proceeded, the view that the sea represents an inexhaustible food storeroom became progressively outdated. The recognition that all fisheries resources are finite, had set the scene for the conventional archetypal of fisheries management programs. Consequently, fisheries assessment programs progressively became more common, reflecting the ever-growing consciousness of mankind in sustainability, establishing the status of a resource and determine the levels at which it may be sustainably exploited. Stock estimates, in addition to environmental, economic, sociological and political considerations, are then used to suggest management strategies for the fishery (King, 1995; Haddon, 2001; Finley, 2009).

Where extensive data have been collected and population parameters have been estimated, it may be possible to estimate a relative index of abundance. Following the development of a fishery, a permanent system of data collection may be used to monitor the healthiness of a fishery and to determine the effectiveness of management strategies (King, 1995; Haddon, 2001).

Management strategies for fishing resources have been based on the monitoring of population structure and the dynamics of the commercially-exploited stocks, including the degree of exploitation. Catch and fishing effort information are basic data requirements, and these may be supplemented by other measures, such as a regular collection of length-frequency data. Although annual catches will fluctuate to a greater or lesser degree depending on the target species, a trend of falling catch rates and decreasing length at capture may provide evidence that the fishery is being exploited beyond the sustainable rate (King, 1995; Haddon, 2001).

Stock assessment usually involves estimating parameters of some form of population dynamics model. Generally, it is performed by fitting it to research data and using the results of the fitting process to estimate quantities that are of interest to decision makers. A variety of data types can be used when fitting stock assessment models. However, the data generally must include information on at least the removals due to harvesting and an index of relative abundance (King, 1995; Haddon, 2001).

1.1. CPUE as a measure of abundance

Although the index of abundance should, ideally, be based on fishery-independent data collection, *i.e.*, when fisheries scientists collect fisheries information independent of commercial or recreational fishing operations, such as surveys in controlled scenarios, these are extremely costly to collect, hence the majority of the studies of this nature are based on fishery-dependent data (Maunder & Punt, 2004). The most common source of fishery-dependent data is catch and effort information from commercial or recreational fishers, usually summarized in the form of catch-per-unit-of-effort (CPUE) or catch rate (Maunder & Punt, 2004; Maunder *et* *al.*, 2006). The primary assumption behind a CPUE-based abundance index is that changes in the index are assumed to be proportional to changes in the actual stock abundance, thus being considered a relative index of abundance (Hinton & Maunder, 2003; Maunder & Punt, 2004; Ortiz & Arocha, 2004; Carvalho *et al.*, 2014; Hoyle *et al.*, 2014; Bernasconi *et al.*, 2015).

The use of CPUE as an index of relative abundance assumes that catch is proportional to the product of fishing effort and fish population density: $C = q\mathrm{EN}$, where E is the fishing effort expended, N the population density, and q the fraction of the abundance that is captured by one unit of effort, often known as the catchability coefficient (Hinton & Maunder, 2003; Campbell, 2004; Maunder & Punt, 2004; Maunder *et al.*, 2006).

The latter equation can be rearranged to form the connection between CPUE and abundance: $\mathrm{C/E} = q\mathrm{N}$. This equation can be generalized from a small patch fished by a single fisher to the entire population fished by a large fishing fleet as long as q remains constant over time, independent of space, population size and fishing fleet. However, this assumption is unrealistic since q is seldom constant over the entire exploitation history, being influenced by spatial and temporal aggregation of fish, changes in fishing power, gear selectivity, environmental variability, and dynamics of the population or fishing fleet (Maunder & Punt, 2004; Ortiz & Arocha, 2004; Venables & Dichmont, 2004; Maunder *et al.*, 2006; Carvalho *et al.*, 2014; Hoyle *et al.*, 2014). Therefore, in order to assume that CPUE is proportional to abundance, it is important to account for changing features in which a stock exploitation is susceptible.

1.2. Methods of standardizing CPUE

Due to the importance of CPUE in many stock assessments and the assumption that CPUE is proportional to abundance, it is important to revise this relationship. Consequently, the ability to use catch rate data as an index of abundance depends on being able to adjust for the impact on catch rates over time of explanatory variables (also called covariates, predictors or even independent variables) other than abundance, until then not accounted for. This process is often referred to as 'catch-effort standardization' (Campbell, 2004; Maunder & Punt, 2004; Maunder *et al.*, 2006; Bentley *et al.*, 2011; Hoyle *et al.*, 2014; Bernasconi *et al.*, 2015).

Several methods for CPUE standardization exist, involving fitting statistical models to the catch and effort data. One of those are linear models, which form the core of classical statistics and is still the basis of much of statistical practice. Multiple linear regression attempts to model the relationship between two or more explanatory variables and a response variable by fitting a linear equation to observed data (Venables & Dichmont, 2004; Montgomery, 2013). Every value of the independent variable x is associated with a value of the dependent variable y. It is defined as: $Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon$, where β_0 is the intercept, β_j are the coefficient effects and ε is the error term (Montgomery, 2013), also called noise term. Therefore, it assumes that predictors are continuous and have established a linear relationship with the response (also continuous) via a link function (*i.e.*, the connection between the linear predictor, η, and the mean of the distribution, μ) (Venables & Dichmont, 2004) called *identity* $[g(\mu_i) = \eta_i)]$, the predictors are independent of one another (*i.e.*, one variable does not provide information on another) (Zuur *et al.*, 2009), the variance is constant, and assuming a normally distributed error $[e_i \sim N(0,\sigma^2)]$ (Venables & Dichmont, 2004; Montgomery, 2013). This method, although very straightforward and easy to compute, does not accommodate for different types of error distribution since it assumes linearity between the predictors and the response (Venables & Dichmont, 2004; Montgomery, 2013).

Another method for CPUE standardization is the Generalized Linear Model (GLM). It is a flexible generalization of ordinary linear regression that allows the response variable to have a Gaussian but also other types of error distributions from the exponential family. It allows the linear model to be related to the response variable via a link function and states that the magnitude of the variance of each observation to be a function of its predicted value (Campbell, 2004; Maunder & Punt, 2004; Venables & Dichmont, 2004; Montgomery, 2013). It can be formulated as follows: $Y = g^{-1}(\beta_1 x_1 + \beta_2 x_2 \ldots + \beta_n x_n) + \varepsilon$, where each component of Y is independent, assuming error distribution forms other than the normal distribution (*e.g.* Binomial, Poisson, Gamma, etc.), the n predictors are combined to give the “linear predictor”, and the relationship between the random and systematic components is specified via a link function, $g(\mu) = \mu$, that is differentiable and monotonic (Maunder & Punt, 2004; Venables & Dichmont, 2004; Montgomery, 2013). It is therefore important to evaluate the appropriateness of the distribution assumed for the errors in the dependent variable of the standardization procedure. As such, other than the normal distribution, several error distributions can be assumed, namely:

a) *The Poisson distribution*. Data is often collected in counts. Poisson counts are the number of occurrences of some event in a certain interval of time (or space). The link function is the *log link*: $\eta = \log(\mu)$, and the variance function is $v(\mu_i) = \mu_i$. Poisson models with log links are often called *log-linear models* and are used for frequency data (Venables & Dichmont, 2004; Montgomery, 2013).

b) *The binomial distribution*. A binomial distribution (also called *Bernoulli* distribution) is most useful for estimating expected cell counts from a given model. The response is conventionally taken as the relative frequency and the mean is a probability, situated between 0 and 1. Hence, the link function must map the real line into the closed interval [0, 1]. The link function is called *logistic* or *logit* and is formulated as: $logit\,(p) = \ln\,(p_i / 1 - p_i)$, mapping from (0; ∞) and the variance function is $v(\mu_i) = \mu_i\,(1 - \mu_i)$ (Maunder & Punt, 2004; Venables & Dichmont, 2004; Montgomery, 2013).

c) *The gamma distribution*. The gamma distribution is useful for continuous data with non-constant error. The link function is called *inverse,* formulated as: $\eta = 1/\mu$. The variance function is $v(\mu) = \mu^2$ and the scale parameter, φ, is generally unknown. (Venables & Dichmont, 2004).

Other error distributions are possible in GLMs (*e.g.* Negative Binomial, Tweedie, Inverse Gaussian, among others), mostly characterized by providing options exerting greater flexibility in analysing a given data set for predetermined statistical examination (Hinton & Maunder, 2003), though beyond from the scope of this thesis.

Catch and effort data often include catches with high proportions of observations in which the catch is zero, even though effort is recorded as non-zero. This is particularly the case for less abundant species and for bycatch species. The presence of many zero observations can invalidate the assumptions of the analysis and jeopardize the integrity of the inferences if not properly modelled. It is then desirable to deal with zero observations. The simplest way is to ignore them, which might be appropriate if zero catches are the cause of gear malfunction or other unforeseen event, though this may have undesirable effects such as positively biasing the standard catch rates, but to a different extent each year (Hinton & Maunder, 2003; Maunder & Punt, 2004; Ortiz & Arocha, 2004; Venables & Dichmont, 2004).

One of the most common ways to deal with zero catches is to log-transform the data and introduce a constant to each observation, if the most normal-like distribution of residuals is provided by this operation. This transformation would stabilise the variance and produce an *identity* link between mean and linear predictor in the transformed scale (assuming a Gaussian error distribution), although the catch-effort standardization may be sensitive to the value of the constant, possibly biasing the standardized response (chosen arbitrarily, but usually defined as equivalent to 10% of the mean catch-rate) (Campbell, 2004; Maunder & Punt, 2004; Ortiz & Arocha, 2004; Venables & Dichmont, 2004; Bentley *et al.*, 2011).

Other methods exist to deal with zero observation, such as: a) statistical distributions that allow for zero observations; b) methods that inflate the expected number of zeros, called the zero-inflated models; c) methods that predict the proportions of positive catches and model the catch rate when the catch is non-zero separately, which is the case of delta approaches (Maunder & Punt, 2004).

Although the great majority of the catch-effort standardizations are based on the application of GLMs, other estimation frameworks can also be applied. In many situations, nonlinear relationships may better describe the relationships between CPUE and explanatory variables. General Additive Models (GAMs) afford greater flexibility in expressing such relationships, significantly expanding the range of possible relationships which may be considered during standardization procedures (Hinton & Maunder, 2003; Venables & Dichmont, 2004). Other methods of standardization are the General Linear Mixed Models (GLMMs). These extend the GLM approach by allowing some of the parameters in the linear predictor to be treated as random variables, in addition to the usual fixed effects (Hinton & Maunder, 2003; Venables & Dichmont, 2004; Maunder & Punt, 2004; Hoyle *et al.*, 2014; Bernasconi *et al.*, 2015).

Overall, the methods used to standardize CPUE are based on predicting catch rate or CPUE, with the goal of providing an index of relative abundance, usually by estimating the year effect. Good prediction of catch rate or CPUE does not necessarily infer good estimation of the relative abundance, but it is generally assumed that the best model provides the best available indicator of relative abundance (Hinton & Maunder, 2003).

1.3. Model selection

A mathematical model of biological data is always a simulation of nature. These models can be purely simulations in which values for all parameters are not estimated but simply given plausible values. Such models can be used to illustrate the implications of a particular idea or model structure. However, when models are descriptive and/or explanatory of a particular situation in nature, it is necessary to estimate values for at least some of the model and data observed from nature. The design of a model, such that it adequately represents the structure of the modelled system, primarily relates to determining which type of model adjusts to any given data, the variables to be selected into the model and the relationships between them (Haddon, 2001).

The goodness-of-fit of a model is a quantity that expresses how well the model is able to account for a given set of observations (Hinton & Maunder, 2003; Vandekerckhove *et al.*, 2014). It addresses the following question: Under the assumption that a given model is a true account of the population from which we have attained a sample, and given the best fitting parameter estimates for that model, how well does our sample of data approve the model? Thus, goodness-of-fit must be balanced against model complexity in order to avoid overfitting (or overparameterization) - that is, to avoid building models that well explain the data at hand, but fail in out-of-sample predictions (Vandekerckhove *et al.*, 2014). Considering the principle of parsimony, *i.e.*, a good principle to explain a phenomenon is using the simplest hypotheses that can be established, provided this does not contradict the data in a significant manner, or in other words, simpler models should be preferred over complex ones (Vandekerckhove *et al.*, 2014), researchers are forced to abandon complex models that are tweaked to the observed data in favour of simpler models that can generalize to new data sets (Hinton & Maunder, 2003; Maunder & Punt, 2004; Zuur *et al.*, 2009).

Several methods for model selection exist, being the most commonly used the information-theoretic methods, such as the Akaike Information Criterion (AIC) (Akaike, 1973) and the Bayesian Information Criterion (BIC) (Schwarz, 1978). These are used to determine which model best fits the data at hand, in a comparison fashion between one and another. The models do not need to be nested and can have the same number of parameters or different number of parameters. Models with smaller AIC and BIC values, *i.e.*, with the smallest expected information loss between reality *f* and model *g*, are preferred to those with larger values (Hinton & Maunder, 2003; Maunder & Punt, 2004; Vandekerckhove *et al.*, 2014).

Other tests are based on maximum likelihood. The likelihood ratio test (LRT) examines if a more complex model, one with more estimated parameters, fits the data significantly better than a less complex model. The LRT requires that the models be nested. Nested means that the less complex model is equivalent to the more complex model with one or more of the parameters fixed (usually at zero, one, or equal to another parameter). The test criterion is based on the Chi-square distribution with the degrees of freedom equal to the difference between the number of parameters in the models (Hinton & Maunder, 2003; Maunder & Punt, 2004; Vandekerckhove *et al.*, 2014).

Irrespective of how closely one can produce sound statistical analysis, followed by comprehensive model selection procedures to describe a phenomenon, there is no logical or automatic implication that the model chosen is necessarily the best representation of the system being modelled. Uncertainty is an unpleasant commonplace in abundance estimations and how best to approach it is a growing and vital part of fisheries modelling (Haddon, 2001).

1.4. Objectives

In light of the continued widespread use of catch and effort data, it is important that fisheries scientists and managers have a good understanding of the relationship between catch rates and indices of fish abundance and the factors that may unduly influence this relationship (Campbell, 2004).

The deepwater fishes *Aphanopus spp.* are of great importance for Madeira Archipelago. Its fishery employs directly and indirectly thousands of people, heavily contributing with its social, cultural and economic relevance. Dating back to the 17th century (Gordo *et al.*, 2009), this artisanal fishery is typical of Madeiran communities that depend on the sea for their livelihood, where the product is marketed generally fresh in local markets. Hence, the exploitation of this resource must be sustainable if continuation of its exploration is to endure.

The difference between catches and landings unfortunately creates further uncertainty if no information about discarding or other losses of fish at sea is available. Since the longline fishery has a much reduced bycatch and almost zero discards of the target species, given that the non-target species with no commercial value are not landed and are reused as bait (Farias *et al.,* 2013), it was assumed that the amount of captures is practically equal to the amount of landings. Hence, and following the suggestion of Gordo *et al.* (2009), LPUE data was analysed and used in this study.

Several approaches were opted in order to produce the best statistical analysis that would fit the available data, always considering the discrepancy between predictions and reality. Options were taken based on numerous authors with proven knowledge in the Madeiran fishing industry features and statistical modelling. Accordingly, the objectives for this part of the thesis are as follows:

1) Perform a standardization of commercial LPUE data of fish landed in Madeira Archipelago, in the period between 2008 and 2015;
    - Identify the explanatory variables with significant influence in the variability of the nominal LPUE;

- Select the most parsimonious model in which the nominal LPUE standardization is performed;
- Plot nominal LPUE vs. standardized LPUE and discuss differences between both estimates.

2) Characterize briefly the evolution of the black scabbard fishing fleet in Madeira.

2. Materials and methods

2.1. Data source

Commercial *Aphanopus spp.* fisheries data landed at Funchal harbour were obtained annually, on an eight-year period, from 2008 to 2015. The data analysed derives from different regions inside the Madeiran EEZ, located within the FAO CECAF 34.1.2 area but also from adjacent waters in Canary Islands and Azores since the fishermen usually exploit more distant fishing grounds.

The data is a part of the collection campaigns in which the DSI gathers as an integrated instrument of the PNRDP. Its purposes are related to the European Data Collection Framework (DCF) in which establishes a number of guidelines aimed to regulate fishing quotas among EU countries, monitor fishing effort across fleets and ultimately to manage population units under pressure.

The fishery data relies on information provided by the fishing community, each time a vessel returns to port to land fish. Hence, it is considered fishery-dependent data. Although not ideal to perform this kind of survey, it is the most common procedure to calculate nominal LPUE and standardize it. Fishery-independent data are less common since it is obtained in the absence of any fishing activity. It relies on scientific expeditions, governmental surveys and other activities of that sort, with controllable fishing procedures, in which every single detail of the fishing process is carefully monitored being extremely costly and also difficult to collect (Maunder & Punt, 2004).

Since the data analysed is fishery-dependent, some features of the data are not well documented, which most of them regards to effort units. As the amount of fish landed at port is controlled by the authorities, the amount of fish landed is regulated but several features of the fishing procedure are not, namely geographical coordinates of the fishing grounds, type of bait used (may differ affecting the outcome of the catch), precise number of crew members in each trip, precise numbers of hooks (most records may not be entirely correct and some even lack), and further.

The available data covers an array of fishery related features such as landing date by day, week, month and year, the landings per weight, in kilograms, vessel and their technical characteristics such as length-over-all (LOA, in m), gross tonnage (GT) and engine power (POW, in Kw). Other features include the type of gear and several units of effort, such as fishing days (days spent fishing), days spent at sea (from the moment the vessel leaves port to the moment it arrives), fishing operations (including hauls and gear deployment) (Bordalo-

Machado & Figueiredo, 2009), fishing trips (all the moments related to fishing, including coming and returning to fishing grounds before coming to port definitely), number of hooks, gear soaking time (hrs) and hours at sea.

A preliminary analysis was conducted and information of the database was filtered to detect obvious errors and to avoid misinterpretations and erroneous conclusions. Any violations of the model assumptions and other statistical problems were prevented as best as possible and conclusions were made based upon those results.

2.2. Fleet characteristics description

The chronological changes in vessel characteristics and fleet size are described in the fleet characteristics section. The number of vessels considered for the analysis were the ones with at least one landing event of *Aphanopus spp.* in the period of 2008-2015.

The data set, provided by the vessel owners each year, covered individual information on each of the vessels' features, from GT, POW and LOA, pooled from the period mentioned above. Average and standard deviation estimates of GT, POW and LOA were calculated using *Aphanopus spp.* landings data by vessel. The evolution of the fleets' characteristics is then approached, referencing some features of the fishing procedure directly related to the vessels' technical characteristics and other features deemed worthy of mention.

2.3. Model selection and fit

Numerous standardization models have been conceived in order to accommodate the different array of fishery data. The most common method to standardize catch and effort data is the application of Generalized Linear Models (GLMs) (Maunder & Punt, 2004; Ortiz & Arocha, 2004). Another common method is simply by using a classic linear model (LM). The main differences between both models is that the GLM accepts data where the error distribution is non-normal, hence accepting several link functions from the exponential family, conferring greater flexibility (Maunder & Punt, 2004; Ortiz & Arocha, 2004). Since the data used in this study is normally distributed, there was no need to use a GLM, hence a simple multiple linear regression model was used.

Considering that the data is highly skewed due to its fishery-dependent nature, it is important to evaluate the appropriateness of the distribution assumed for the errors in the dependent variable of the standardization procedure carefully. Data transformation had to be performed in order to ensure normality. Hence, following the suggestions of Ortiz & Arocha (2004), Bordalo-Machado & Figueiredo (2009), which followed the same log-transformation response for *A. carbo* fishery, and Zuur *et al.* (2009), a log-transformation of the dependent variable was performed, assuming that the logarithm of the response has a normally distributed error [$\epsilon \sim N(0,\sigma^2)$], thus ending with a log-normal model.

However, assuming normality of the data through this method raised another question. Many authors add a constant in log-transformed data to compensate for the log-transformation (Hinton & Maunder, 2003; Ortiz & Arocha, 2004). Considering that the mid-water drifting longline fishery is very specific, highly selective, with very low bycatch numbers observed and almost zero discards of the target species (Farias *et al.,* 2013), no constant was added. In addition, since the response variable corresponds to landed catch in weight, no zero observations are present since no fishing vessel returns to port reporting and effectively landing zero catches (rare but may happen to cut losses). Therefore, the problem of zero landings does not apply in this case, hence upon log-transformation, no constant was added because no zero landings had to be compensated.

The use of nominal LPUE as an index of relative abundance assumes that all factors affecting the landings rate (in this case, catch rate through landings) have remained constant over time (Campbell, 2004). Nominal LPUE is generally calculated by dividing the landings (weight) per unit of effort while neglecting many other variables that influence the total amount of fish retrieved from the ocean, contributing to an unreliable abundance estimate. Consequently, it is essential to standardize nominal landing data in order to account for all the variables that have a significant impact in the abundance estimate (Hinton & Maunder, 2003; Campbell, 2004; Maunder & Punt, 2004; Ortiz & Arocha, 2004).

Since the objective is to standardize nominal LPUE, a standardization model was conceived in order to evaluate the performances of several explanatory variables for predicting the variability of the response variable. Based on previous reference studies for this particular fishery targeting deepwater species in Madeira, such as Reis *et al.* (2001), Bordalo-Machado & Figueiredo (2009) and STECF (2014), nominal effort was established as the number of hooks and nominal LPUE was calculated as the amount of fish landed (kg) per thousand hooks and attributed as the response variable.

Succinctly, the model chosen was a classic multiple linear model, in which the response variable is continuous, the link function, *i.e.*, the connection between the linear predictor, η, and the mean of the distribution, μ (Venables & Dichmont, 2004), is *identity* and a log-normal error distribution was assumed [$\epsilon \sim N(0,\sigma^2)$].

2.4. Diagnostic statistics

All statistical techniques have in common the problem of 'rubbish in, rubbish out'. In some methods, for example, a single outlier may determine the outcome of the results and subsequent conclusions. Heterogeneity (differences in variation) may cause serious problems in linear regression and analysis of variance models, amongst others. Collinearity can bring dubious results in model formulation as well as independency of the observations of the response variable. Thus, the underlying question of which covariates are driving the system is essential if the outcome is a model that approximates to reality (Zuur *et al.*, 2009).

Regarding the selection of explanatory variables, based on prior knowledge, an analysis and subsequent data treatment can lead to unforeseen and unclear conclusions, and having the analytical flexibility to adjust to a circumstance at hand requires a thorough understanding of the constraining assumptions imposed by a given data set (Zuur *et al.*, 2009; Zuur & Leno, 2016). Before selecting a model to use for standardization, several steps had to be taken in order to avoid violations of the model assumptions. Hence, an overall diagnostic analysis was performed, following the suggestions made by Maunder & Punt (2004) and Zuur *et al.* (2009).

Collinearity, *i.e.* the existence of correlation between covariates (Maunder & Punt, 2004; Zuur *et al.*, 2009; Zuur & Leno, 2016), had to be overcome. If ignored, one is likely to end up with a confusing statistical analysis and problems similar to those of over-fitting, in which nothing is significant, but where dropping one covariate can make the others significant, or even change the sign of estimated parameters (Maunder & Punt, 2004; Zuur *et al.*, 2009). In that sense, a "dummy" data frame was created in which all covariates were correlated amongst each other. The selection of one covariate over another was based by the correlation coefficient. Following Zuur *et al*. (2009), if a correlation coefficient between two correlated covariates were higher than 0.8, this strong correlation had to be addressed by removing one of the covariates, most of which based on prior biological knowledge of the influence on the response variable (*Appendix B.1*).

A crucial assumption of most statistical techniques is that observations are independent of one another, which means that one covariate should not provide information on other covariate, hence being independent from one another (Zuur *et al.,* 2009; Zuur & Leno, 2016). Any clear sign of pattern signifies a sign of dependence and those that showed those signs were removed from the model.

Another important step in formulating the model concerns the existence of outliers. It is generally defined as an observation that has relatively large or small value compared to the majority of observations (Zuur *et al.*, 2009; Zuur & Leno, 2016). Following the suggestions of Zuur *et al.* (2009), due to the fact this is indeed a large data set, in which thousands of records on an eight-year period are covered, such observations were omitted. Equally important is the homogeneity of variance assumption. Verification of homogeneity was made by plotting the residuals vs. fitted values. No violation for this assumption was found (A*ppendix B.2*).

2.5. Evaluated variables

Considering all the steps mentioned above, the data exploration led to the exclusion of several explanatory variables in which violation of one or more assumptions was confirmed. The selection of explanatory variables was evaluated by an information-theoretic method, the Akaike Information Criterion (AIC), on a backward stepwise selection (Akaike, 1973). The AIC is a measure of quality of statistical data, in which it provides the means for model selection. The AIC penalizes for the addition of parameters, and thus selects a model that fits well but has a minimum number of parameters, favouring simplicity and parsimony. Thus, the model with the lowest AIC value is the preferred one (Maunder & Punt, 2004; Carvalho *et al.*, 2014; Vandekerckhove *et al.*, 2014; Bernasconi *et al.*, 2015).

The process was done by pruning from a model with all the explanatory variables that, based on *a priori* knowledge of the data, had an influence on the variability of the response. Removal of predictors and interactions was done one at a time through the "*drop1*" function on RStudio, on a backward stepwise manner, until all predictors had an AIC value higher than the model's AIC. Therefore, a model which represented as accurate as possible the circumstances at hand was chosen. In order to avoid over-fitting and following the suggestions of Maunder & Punt (2004), no interactions were added because many of them are hardly explainable and most importantly, they deviate our attention from the main predictors, whom importance should not be undervalued, as they offer much more than the interactions themselves.

Consequently, and a part of the model pruning explained in previous paragraphs, the variables excluded from the models are as follows:

Fishing trips = Corresponds to the number of times a vessel would go out to sea and return to disembark fish. This variable was abandoned due to the independence violation with *Fishing Days*.

Gear type: Corresponds to the type of gear deployed when fishing. Abandoned due to being non-significant in explaining the variability of the response variable. Mainly explained due to the fact that the fleet uses always the same type of gear.

LOA: Corresponds to the length-over-all of the vessel. Abandoned due to collinearity with *Gross Tonnage*. It was decided to remove because it makes more sense in terms of the amount of catch that can enter inside the vessel. A heavier vessel will have more equipment and possibly crew to handle more catch, influencing much more the response variable than *LOA*.

Hours at Sea: Corresponds to the number of hours spent at sea. Abandoned due to collinearity issues with *Days at Sea* and *Fishing Days*. Since the associated error is much greater in *Hours at Sea* than the other two (a fisherman may well misreport the hour but hardly that will happen to the day), this one was removed from the model.

Fishing days: Highly collinear with *Days at Sea*. It was abandoned because Days at Sea relates to the time spent fishing and to the time spent steaming to the fishing grounds, hence directly related to the effort involved in obtaining a specific catch. So its broader and more inclusive relation to catches was the main factor in choosing it for the model.

Ultimately, explanatory variables that reduce the unexplained variability in the response variable were selected as part of the model (Maunder & Punt, 2004). After several preliminary attempts, several explanatory variables were selected, as shown in *Table 3.1*.

Table 3.1. Explanatory variables used in the model hypothesized to affect landing rates of *Aphanopus spp.* in the longline fishery in Madeiran waters.

Explanatory variables	Type	Levels	Description
Year	Categorical	8	2008-2015
Month	Categorical	12	From January to December
Soaking time	Continuous	---	Soaking time of the gear, defined as the time between end of setting and beginning of hauling
Engine Power (POW)	Categorical	12	Vessels’ engine power in Kw (< 25; 25-50; 50-75; 75-100; 100-125; 125-150; 150-175; 175-200; 200-225; 225-250; > 250)
Gross Tonnage (GT)	Categorical	10	Vessels’ registered gross tonnage (< 5; 5-10; 10-15; 15-20; 20-25; 25-30; 30-35; 35-65; > 65)
Fishing operations	Continuous	---	Number of gear deployments and hauls
Days at sea	Continuous	---	Number of days spent at sea

2.6. LPUE standardization

After applying a systematic data exploration and model selection techniques, the most parsimonious model was selected in order to explain the variability of the response. The model was formulated following suggestions of Zuur & Leno (2016). It is as follows:

$$\mathrm{Log}(\mathrm{LPUE}_{i,j,k,l,m,n,o}) = \mu_0 + \beta_1(\mathrm{Year}_i) + \beta_2(\mathrm{Month}_j) + \beta_3(\text{Days at sea}_k) + \beta_4(\text{Fishing operations}_l) + \beta_5(\mathrm{GT}_m) + \beta_6(\mathrm{POW}_n) + \beta_7(\text{Soaking time}_o) + \varepsilon_{i,j,k,l,m,n,o},\ \varepsilon \sim \mathrm{N}(0,\sigma^2)$$

where,

$\mathrm{Log}(\mathrm{LPUE}_{i,j,k,l,m,n,o})$: log-transformed response [landings (Kg) per 1000 hooks] in year *i*, month *j*, days at sea *k*, fishing operations *l*, GT *m*, POW *n*, soaking time *o*;

μ_0: the intercept;

$\beta_1, \ldots, \beta_7$: denotes the parameters to be estimated for each effect;

Year_i: main effect of year *i* (*i* = 2008, …, 2015)

Month_j: main effect of month j (j =1, …, 12);

Days at sea_k: main effect of days at sea k (k = 1, …, 25);

$\text{Fishing operations}_l$: main effect of fishing operations l (l = 1, …, 23);

GT_m: main effect of the vessel gross tonnage m (m = <5, …, >35);

POW_n: main effect of the vessel engine power n (n = <25, …, >250);

Soaking time_o: main effect of the gear soaking time o (o = 4, …, 48);

$\varepsilon_{i,j,k,l,m,n,o}$: the normally distributed error term.

In order to prevent a biased estimation, the problems of over- and underfitting was a concern and all predictors included in the model were cautiously examined and only the absolute significant ones, with proven influence in the index were included. After choosing the model, the standardized LPUE values were calculated, through the "*predict*" function in the package "*dplyr*" of RStudio, on a yearly time-scale. Subsequently, the values obtained were then back-transformed by simply e^x for each value, in order to return the log-transformed data and be able to compare in equal terms with the nominal LPUE. The same procedure was applied for the explanatory variables that effectively had higher size effect on the variability of the response, namely GT and fishing operations, in which standardized LPUE values were calculated and plotted with nominal LPUE values for each predictor. Thus, standardized LPUE values were plotted not only in a time scale but in an effort unit scale as well.

After choosing the model, the effects size, *i.e.*, refers to the magnitude of the result as it occurs, or would be found, in the population (Elis, 2010), of each predictor had to be calculated in order to complement the results of the model. Following suggestions from Elis (2010), the *Omega Squared* (ω^2) method was chosen since it is a less unbiased alternative in comparison to other size effect estimation methods. Therefore, using the values from the ANOVA table, the effect sizes were calculated using the formula, as follows:

$$\omega^2 = SS_{effect} – (df_{effect} \times MS_{Error}) / SS_{Total} + MS_{Error} \qquad \text{(Equation 3.1)}$$

where,

SS_{effect}: sum of squares of the effect;

SS_{Total}: total sum of squares;

df_{effect}: degrees of freedom of the effect;

MS_{Error}: mean square of the error.

Once the best model was selected and LPUE standardized values were calculated, the last part of the strategy was to compare the standardized model's LPUE to the nominal LPUE values and infer trends among the years in which the study leaned upon. This made possible to understand if the model is realistically describing LPUE trends and which variables are causing discrepancies among the nominal LPUE and standardized LPUE. Also, by understanding the influence certain variables have on LPUE trends, several changes can be made in order to improve this fishery, in terms of fishing success and conservation issues. In essence, the standardized LPUE reflects a more reliable abundance estimate upon which scientists, fishermen and decision makers can work with to ensure this valuable resource maintains its key role in Madeiran economy and culture.

All tests were done in order to narrow down the skewness of the data and provide the best statistical analysis possible. The steps regarding the diagnostic statistical analysis were based upon suggestions and criterions following Maunder & Punt (2004), Venables & Dichmont (2004) and specially Zuur *et al.* (2009) through its data exploration protocol. In all statistical tests, a significance level of 95% was applied ($\alpha = 0.05$). Statistical tests were performed using the software RStudio, an integrated software of R version 3.2.2 (R Core Team, 2015).

3. Results

3.1. Fleet description

In the period of time covered, the fleet suffered a reduction in vessel numbers. *Table 3.2.* describes the descriptive statistics of the fleet. In 2008, 34 vessels actively landed fish in the archipelago. The number of vessels progressively decreased with time, dropping to 23 vessels in 2015. The most striking difference is the GT, in which decreased by more than 5 tonnes, which is not surprising since less vessels landed *A. carbo*. LOA and POW remained basically unaltered.

On average, each vessel used 525 thousand hooks in 2008, contrasting to 664 thousand hooks in 2015. Also, on average, each vessel spent 161 days at sea in 2008, whereas in 2015, it increased to 176 days per vessel, varying with landing performances. As landings decrease, fishing effort generally increases to compensate the lack of captures.

The vessel with the greatest landings in the period covered was the vessel "*Navego*", whose landing surpassed 1500 tonnes. The other vessels whose landings were also very substantial (> 1000 tonnes) are the vessels "*Alexandre Coelho*", "*Ricardo Cristina*", "*Tiago José*" and "*Gabriel*". These vessels represent some of the largest and heaviest of the fleet, which may explain such significance in the landings across this period. The fishing gear and the fishing operation, *i.e.*, deploying the gear, hauling it and storing the captures, maintained its methods. Steel Nº 5 and 6 hooks are still used and the bait is commonly salted squid slices (*Ommastrephes* sp.), but also filets of horse mackerel (*Trachurus picturatus*) and mackerel (*Scomber colias*) (Bordalo-Machado *et al.*, 2009).

Table 3.2. Summary of the evolution of the fleet characteristics of Madeiran vessels. LOA, length-over-all (m); GT, gross tonnage; POW, engine power (Kw).

Year	Statistic	Nº vessels	LOA	GT	POW
2008	Mean	34	12.31	25.11	135.66
	Std. Dev.		3.64	21.29	75.78
2015	Mean	23	12.43	19.95	134.03
	Std. Dev.		3.61	13.94	82.61

3.2. Model deviance explained and effect sizes

The model selected for LPUE standardization had as significant predictors year, month, days at sea, fishing operations, GT, POW and gear soaking time. The results of the linear model are shown in *Table 3.3.*

Table 3.3. Results from the F-test of the predictors for the linear model.

Response variable *Log[Nominal LPUE (kg/1000 hooks)]*						
Factors	df	Sum Sq.	RSS	AIC	F value	Pr(>F)
<none>/(Intercept)			2800.6	-1994.2		
Year	7	57.195	2857.8	-1918.0	12.895	< 2.2e-16
Month	11	82.048	2882.7	-1887.3	11.772	< 2.2e-16
Days at sea	1	69.857	2870.5	-1886.3	110.249	< 2.2e-16
Fishing operations	1	114.005	2914.6	-1818.2	179.924	< 2.2e-16
GT	8	244.695	3045.3	-1636.4	48.273	< 2.2e-16
POW	10	110.424	2911.1	-1841.6	17.427	< 2.2e-16
Soaking time	1	15.762	2816.4	-1971.2	24.877	6.346e-07

The model explained 31% of the total variability of the nominal LPUE. The diagnostics residuals plot and the AIC indicated that the lognormal model was most appropriate to evaluate the factors affecting the variability of nominal LPUE. The residuals patterns showed some deviation from the normal distribution, mainly at the lower end, reflecting some uncertainties of very small LPUE estimates (*Appendix B.2*). Overall, the results obtained were not far from expected under normal error distribution assumption, suggesting a reasonably good fit.

All the variables tested were significant in the model, shown in the ANOVA analysis in *Table 3.4*. The AIC from the model is higher than any AIC from the predictors, indicating that all predictors included in the model fulfil the predetermined requirements. The relative contribution from each variable in the total explained deviance showed that GT (41.8%) was the most important factor, followed by fishing operations (16.7%) and year (15.1%). The predictors that explained the least of the variability of the response were days at sea (8.9%), POW (8.8%), month (7.1%) and soaking time (1.3%).

Table 3.4. Results of the ANOVA test.

Response: *Log[Nominal LPUE (kg/1000 hooks)]*

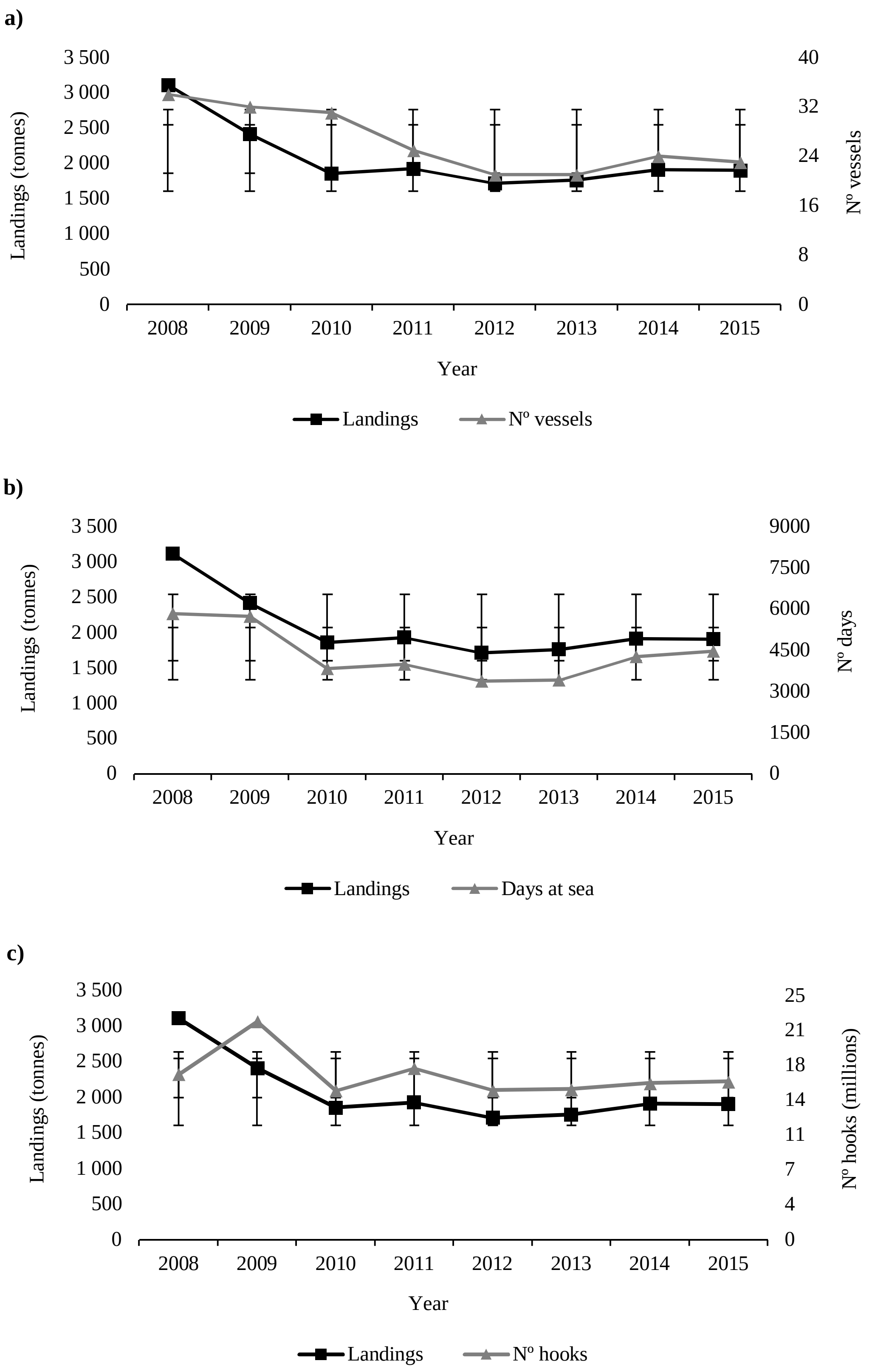
Factors	df	Sum Sq.	Mean Sq.	F value	Pr(>F)
Year	7	194.53	27.790	43.858	< 2.2e-16
Month	11	89.25	8.113	12.805	< 2.2e-16
Days at sea	1	113.91	113.313	178.833	< 2.2e-16
Fishing operations	1	210.10	210.100	331.584	< 2.2e-16
GT	8	527.20	52.720	83.204	< 2.2e-16
POW	10	110.39	11.039	17.421	< 2.2e-16
Soaking time	1	15.76	15.762	24.877	6.346e-07
Residuals	4420	2800.63	0.634		

3.3. Landing trends

Total landings were plotted with several units of effort to understand the trends characterizing the deepwater fishery in Madeira (*Figure 3.1*). Landings have decreased from 3100 tonnes in 2008 to 1900 tonnes in 2015 approximately, although since 2010 it has stabilised around 1900 tonnes.

Regarding the number of vessels actively reporting landings also decreased, from 34 vessels in 2008 to 23 in 2015, reaching the lowest number of active vessels in 2012 and 2013 with only 21 vessels (*Figure 3.1a*). Concerning the number of days spent at sea, it has also decreased in the past years (*Figure 3.1b*). It attained almost 6000 days spent fishing in 2009 to as low as under 3500 days in 2012, increasing again more than 4000 days in 2015. Considering the effort unit of number of hooks, an oscillatory pattern can be observed (*Figure 3.1c*). More than 21 million hooks were used by the fishing fleet in 2009, decreasing to less than 15 million in 2010 and 2012, raising again to more than 15 million hooks used in 2015. Referencing the number of fishing operations (*Figure 3.1d*), it totalled almost 2900 operations in 2008, decreasing below 2500 in 2010, increasing thereafter the following years, surpassing the 3000 operations mark in 2015.

These numbers indicate that in 2008, on average, each vessel landed 91 tonnes of fish, while spending 172 days at sea, using more than 488 thousand hooks, and conducting 85 fishing operations. In 2015, the scenario changed slightly. Each vessel landed, on average, 83 tonnes of fish, while spending 194 days at sea, using almost 690 thousand hooks, and conducting 135 fishing operations. Accordingly, in this eight-year period, on average, each vessel landed 629 tonnes of fish, while spending 1323 days at sea, using 5 million hooks, and conducting 900 fishing operations.


a)
Landings (tonnes)
3 500
3 000
2 500
2 000
1 500
1 000
500
0
Nº vessels
40
32
24
16
8
0
2008
2009
2010
2011
2012
2013
2014
2015
Year
Landings
Nº vessels
b)
Landings (tonnes)
3 500
3 000
2 500
2 000
1 500
1 000
500
0
Nº days
9000
7500
6000
4500
3000
1500
0
2008
2009
2010
2011
2012
2013
2014
2015
Year
Landings
Days at sea
c)
Landings (tonnes)
3 500
3 000
2 500
2 000
1 500
1 000
500
0
Nº hooks (millions)
25
21
18
14
11
7
4
0
2008
2009
2010
2011
2012
2013
2014
2015
Year
Landings
Nº hooks

d)

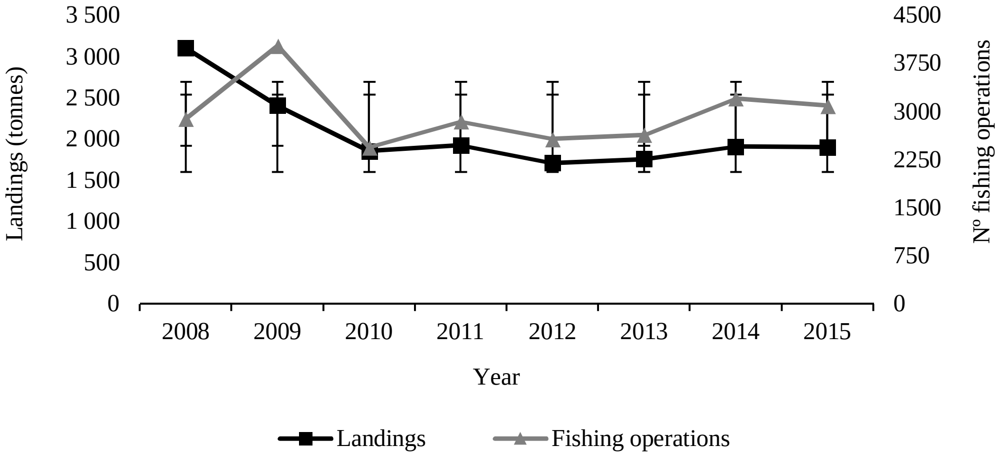


Figure 3.1. Trends of *Aphanopus spp.* landings in Madeira throughout the period of 2008-2015. Each graph describes the relationship of landings with an effort unit: a) landings vs. vessels; b) landings vs. days at sea; c) landings vs. nº of hooks; d) landings vs. nº of fishing operations. Each value is represented by the mean ± SE (error bars).

3.4. LPUE time series assessment

The nominal LPUE values were compared with the standardized LPUE values under a temporal scale from 2008 to 2015, as shown in *Figure 3.2*. The LPUE standardized series shows an oscillatory pattern similar to that of nominal LPUE. Standardized LPUE values are significantly lower than the nominal LPUE, which is in accordance with previous expectations. By removing the variables that did not have an impact on nominal LPUE and by accounting for only the variables that did, standardized values are thus significantly lower.

Nominal LPUE estimates exhibited values on average of 133 kg/1000 hooks in the period in question, while standardized LPUE values exhibited 89.4 kg/1000 hooks. Analysing the differences between both estimates, in 2008 nominal LPUE values were 184 kg/1000 hooks, while standardized LPUE values were equivalent to 142.5 kg/1000 hooks, a difference of around 41.5 kg/1000 hooks between both estimates. The smallest difference was verified in 2011, where nominal LPUE was 119.1 kg/1000 hooks and standardized LPUE was 85.1 kg/1000 hooks, tallying of around 34 kg/1000 hooks difference between both estimates. The largest difference between both estimates was seen the past year, 2015, when nominal LPUE values tallied 134.7 kg/1000 hooks and standardized values reached 81.2 kg/1000 hooks, a difference of around 53.5 kg/1000 hooks.

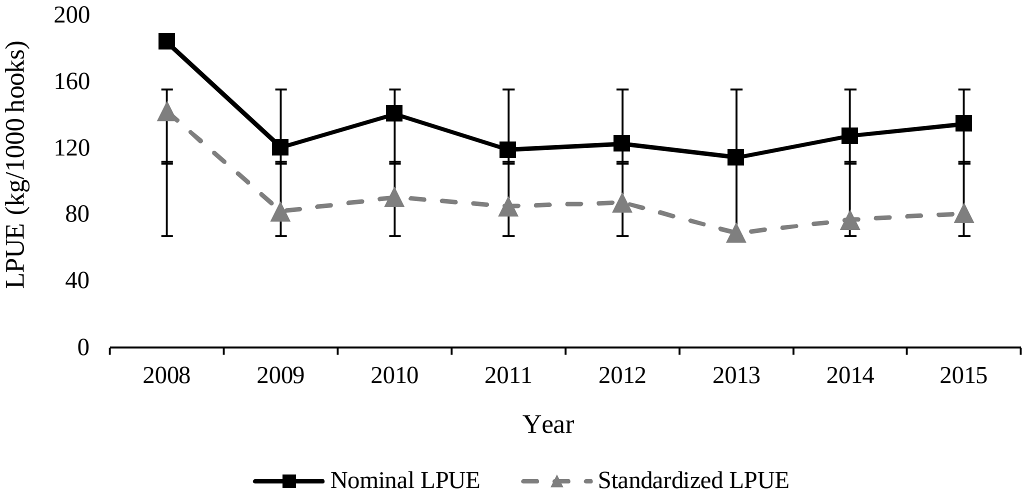


Figure 3.2. Nominal LPUE vs. Standardized LPUE of *Aphanopus spp.* on a yearly basis in the period 2008-2015. Each value is represented by the mean ± SE (error bars).

Figure 3.3. shows the nominal LPUE vs. standardized LPUE estimation for the two variables that contributed the most, beside the year factor, on explaining the variability of the response. These correspond to GT and to the number of fishing operations.

For the GT variable (*Figure 3.3a*), both LPUE estimations exhibited an increasing trend, with the standardized estimation significantly lower than the nominal one. It exhibited its lowest LPUE values in the 5 tonnes class, with the nominal LPUE of 65 kg/1000 hooks and standardized of 46.5 kg/1000 hooks. These values increased gradually since vessels with more volume are able to catch more fish. The class of 35 and >35 tonnes exhibited the highest values of LPUE estimations. Nominal and standardized LPUEs between 213 kg/1000 hooks and 151.8 kg/1000 hooks in the 35 tonnes class respectively, and 205.7 kg/1000 hooks and 145.4 kg/1000 hooks in the >35 tonnes class respectively. The highest LPUE estimation was observed in the 35 tonnes class, where nominal LPUE value was 205.7 kg/1000 hooks and standardized LPUE value was 151.8 kg/1000 hooks. The lowest LPUE estimation was in the 5 tonnes class, where nominal LPUE was 65.1 kg/1000 hooks and standardized LPUE was 46.5 kg/1000 hooks. The greatest difference between both estimates was observed in the 35 tonnes class, with the difference being equivalent to 61.2 kg/1000 hooks. Conversely, the narrowest difference was observed in the 5 tonnes class, with the difference being equivalent to 18.5 kg/1000 hooks between nominal and standardized LPUE.

Regarding fishing operations (*Figure 3.3b*), data was aggregated in classes in order to perform a smoother analysis. Hence, LPUE trends showed an erratic behaviour. Nominal LPUE decreased abruptly in the 16 fishing operation range, only to rise again in higher fishing operation ranges. Standardized LPUE also showed the same decreasing pattern, although less pronounced. The highest nominal and standardized LPUE estimation was observed in the fishing operations class 8, with 140 kg/1000 hooks and 93.6 kg/1000 hooks respectively. The smallest LPUE estimations was in the fishing operations class 16, with 67.2 kg/1000 hooks and 58 kg/1000 hooks respectively. The greatest difference between both estimates was observed in the fishing operations class 20, with nominal and standardized LPUE values of 123.4 kg/1000 hooks and 42.1 kg/1000 hooks respectively, tallying a difference of 81.3 kg/1000 hooks.

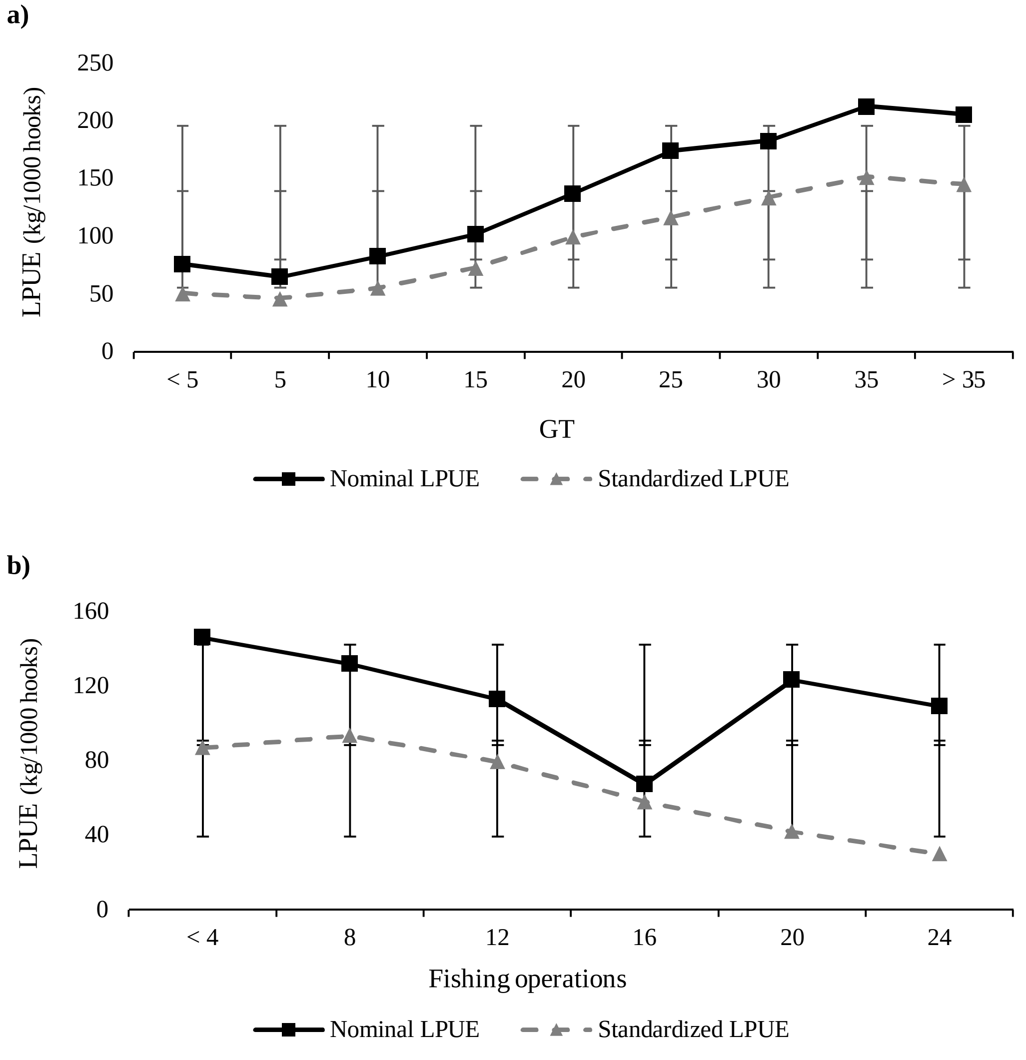


Figure 3.3. Nominal and standardized LPUE estimations for each of the principal variables that explained the variability of the response: a) GT; b) fishing operations. Each value is represented by the mean ± SE (error bars).

4. Discussion

Here it was developed a comprehensive analysis on the deepwater Madeiran fleet technical characteristics, landing rates and fishing effort levels, and a standardized LPUE model was applied to nominal LPUE data for the deepwater fishery in Madeira. The fishery has gone through different periods since its early beginning in the 17th century. Although *Aphanopus spp.* has always been the main commercially exploited species in Madeira alongside with tuna, the fishery has diversified some of its methods in an ever-growing process to keep up with the demand. The variations in landings along different periods (mainly since 1950 where records started) are the result of changes in the behaviour of the fleet during those years, thus indicating that the knowledge, intensity and directionality of effort were changing throughout the fishery history. It is thus beholding such portrayal that this study was devised.

A decreasing trend has become a usual pattern in the number of vessels actively fishing deepwater specimens of *Aphanopus spp.* in Madeiran waters. As reported by Reis *et al.* (2001), the decreasing pattern started in 1980. In 1988 there were 95 traditional vessels, most of them small (around 6 m length). In 2001, the fleet comprised of nearly 40 vessels, averaging 13 m length, 19 tonnes and 112 Kw of engine power, operating with a crew of about nine men. During the next few years, the downward pattern still continued. Bordalo-Machado *et al.* (2009) reported a sharp decrease in the 90's, in which between 1990 and 1995 the number of vessels dropped from 84 to 44. Fleet size continue to decrease to around 30 in the period of 2005-2007, with no significant changes in their technical features.

In this study, the technical features of the vessels have remained very similar to the period described previously, with only the GT of vessels decreasing by an average of 5 tonnes from 2008 to 2015. Engine power and LOA have remained basically unaltered. Also, the number of vessels has also decreased in the period in question, a pattern reported firstly by Reis *et al.* (2001) and later by Bordalo-Machado *et al.* (2009). It appears that the fleet has not recovered since EU funded subsidies were granted to cut down its numbers in the 90's, although recently the fleet suffered further reductions subsidised by such funds in 2009-2010. Many fishing vessel owners beneficiated from those subsidies, as it (over) compensated the fishing exploitation activity itself, and a large number of vessels were scrapped and taken off duty.

The peak of landings of *Aphanopus spp.* was observed in the period of 1997-2001, surpassing the 4000 tonnes each year (DREM, 2015a; Shon, 2015). Since then, landings have decreased by more than half, attaining its lowest values in 2012-2013 of around 1700 tonnes, only to recover to around 1900 tonnes in these past two years of 2014 and 2015. Considering this scenario, it is perfectly reasonable to come to the conclusion that the economic situation of Portugal and of Madeira in particular, with its more restrained budgetary situation, does not allow for new government subsidies. In addition, the inexistence of EU funding and also restrictions in the quota available in the FAO CECAF 34.1.2 area by limiting the fishing effort directed to deepwater fisheries, under regulation of article nº 2347/2002, makes it difficult the development of new vessels in this fishery, only allowing for the already established ones to be maintained, furthering their activity in the sector.

A report from the STECF (2014) studied the deepwater fishery targeting *Aphanopus spp.* of Madeira, reporting a general decline in fishing capacity and fishing effort over the period 2000-2013. The number of vessels declined to around 20, the number of hooks deployed also decreased, meaning that over the time series, individual vessel efficiency has improved through an increase in the average number of hooks deployed.

Following these last results from Bordalo-Machado *et al.* (2009) and the report from STECF (2014), total effort described by the number of hooks has been stable, around 16 million units. Other units of effort have also been considered, but regarding this analysis, it is to reference fishing operations and the amount of day spent at sea. The number of days spent at sea has evolved from 172 to 194 days, and also the number of fishing operations conducted, from 85 to 135 between 2008 and 2015. However, this increase in effort (mostly attributed to a decrease in fleet size of about 32%, which automatically increases individual fishing effort) has not produced better results, since landings have steadily decreased from 3100 tonnes in 2008 to around 1900 tonnes in 2015, representing a decline of 38%.

Generally, the analysis on nominal LPUE estimations and standardization procedures is fairly straightforward and has been done in numerous works. Bordalo-Machado & Figueiredo (2009) focused their attention on studying the deepwater fishery targeting *Aphanopus spp.* in the mainland Portugal continental slope (ICES area IXa) since the 80's. Using log-normal GLM models, a monthly standardization estimation on nominal effort was performed with data covering the period of 2000-2004, and succinctly, comparable shapes were exhibited between the two effort units.

This study comes as a follow up of such examples, although only data from Madeira was standardized. Since the longline fishery has a much reduced bycatch and almost zero discards of the target species (Farias *et al.*, 2013), it was assumed that the amount of captures of *Aphanopus spp.* is practically equal to the amount of landings, so nominal LPUE was standardized as a result, based on a model which, as best as possible, was able to describe some of the variability of abundance in the region.

Selecting an optimum model requires a balance between improving the quality of fit between the model and the data, keeping the model as simple as possible, and having the model reflect reality as closely as possible (Haddon, 2001). As stated by Haddon (2001), the simplest model to describe a natural phenomenon should always be preferred, even if it doesn't always reflect the difficulty in reaching the answer for the simplest thing. As such, the selection of the type of model was a difficult choice. The nature of the data implied right from the start that problems would arise. Therefore, when problems arise, the best solutions often vary. Although this may raise several question marks, as stated by Zuur *et al.* (2009), data transformation was a necessary step since the main goal here was to avoid any assumption violations. Thus, the response was log-transformed in order to reduce the effect of outliers and to achieve normality of the transformed data.

Also, a common procedure when log-transforming data to produce a model, is to add a constant in order to compensate for the transformation (when simply ignoring the zero observations is not an option). Although some still debate about the logic behind this procedure, the constant usually corresponds to 10% of each log-transformed observation, conferring the most normal-like distribution of residuals (Campbell, 2004; Maunder & Punt, 2004; Ortiz & Arocha, 2004; Venables & Dichmont, 2004). Relating to this study in particular, because of the fishery-dependent nature of the data, its associated skewness, and circumstances of this study, past years' landing rates were analysed, not catches. Since the focus is on landings, no bycatch is reported and also no "zero" observations are present, since no vessel returns port with no catches (very rare but may happen to cut losses), even though effort is recorded to be non-zero. Thus, in this study, there was no need to add a constant because no compensation had to be made in order to avoid "zero" landings that, being log-transformed, were accounted as non-zero.

Therefore, the lognormal model was most useful to evaluate the variability of landing rates of *Aphanopus spp.*, while allowing a better understanding of which associated variables were indeed significant and had an impact on the response. The model registered a reasonably good fit, supported by the quantile residuals histograms and QQ-plots, and the distribution fairly close to the Gaussian curve on the log-transformed scale of the response. The AIC was invaluable in terms of model pruning by choosing only the variables that had significant and meaningful impact on the response and excluding variables with unsubstantial contribution to the explicability of the model.

Generally, after analysing the error distribution and the type of model to be chosen, ultimately, one reaches the stage where variables are selected and the model is tested. Regarding the use of interactions, these can occur fairly regularly when standardizing data sets, and when significant and meaningful interactions are discovered, some interesting hypotheses can follow (Maunder & Punt, 2004). However, explaining them can be a troublesome issue, and in many occasions, there may be no rational explanations for their inclusion in the model (Maunder & Punt, 2004). The problem of adding all the factors and interactions in a model, which effectively improves the quality of fit, is that complexity of the model will increase, and as a consequence, its connection to reality may decrease, not fulfilling its purpose to mathematically explain a phenomenon from nature (Haddon, 2001; Maunder & Punt, 2004; Zuur *et al.*, 2009).

As a consequence, the path opted here was towards parsimony, in which the simplest model was preferred in order to explain the impending situation. Interactions were not added mainly because the parameters themselves were the main focus, and also because it is much more interesting to explain the causes of the variability of the response than interactions between them.

In general, the model chosen explained 31% of the total variability of nominal LPUEs. The main factors affecting landing rates were GT (41.8%), fishing operations (16.7%) and year (15.1%), while the variables days at sea (8.9%), POW (8.8%), month (7.1%) and soaking time (1.3%) exhibited lower contributions to the explanatory power of the analysis.

The most important factor in explaining the variability of the response was GT. The GT of a vessel has been described previously to be an important factor in the deepwater fishery targeting *Aphanopus spp.* Bordalo-Machado & Figueiredo (2009) reached similar conclusions when analysing the fleet technical features and their influence in landings off mainland Portugal. In fact, common sense alone would allow us to predict such outcome. After all, a vessels' volume reflects not only the features of the boat but also the amount of equipment it can accommodate. Since the sole purpose of a fishing vessel is to catch the greatest numbers of fish it can possibly carry, heavier vessels thus with greater volumes allow it ultimately to fulfil that goal (Bordalo-Machado, 2006).

This factor can be analysed from more than one perspective. Heavier vessels ultimately allow fishermen to catch more fish, but subdividing this analysis, several features can be explained. For instance, larger fuel tank makes it possible to continue with fishing operations longer than smaller ones, increasing autonomy on one hand and the area covered on the other. Another perspective can be that heavier vessels have larger cargo holds, so more catch can be stored and conserved, increasing revenues and total profits. Yet another perspective could be the amount of crew members it can carry. Heavier vessels can accommodate larger crews since going out to sea, implies larger food and water supplies, more beds for them to rest between fishing operations or between moving from one area to another. Hence, it all sums up in contributing to explain why a vessels' gross tonnage has such a very significant impact on the performance of catch rates, described here through landings.

Following GT as the greatest source of deviance explained, comes the variable fishing operations. Described as the process from the moment where a newly baited longline gear (prepared on land) is deployed into the sea and set, to the moment where another gear previously set in the last 24 - 48h is recovered with the aid of a hauling winch (Bordalo-Machado & Figueiredo, 2009), it was most important in this model. Indeed, it makes sense that this variable has such an influence on the amount of fish retrieved from the ocean. Fishing operations, as described previously, augment the chances of catching greater quantities of fish by performing more of these operations. Simple logic can able any persons' mind to reach the same conclusion. As more operations such as deploying gear and hauling it are performed, the greater chances there is to increase captures. Also, it is highly associated with the vessels' weight, since heavier boats enable the loading of more equipment, and thus more fishing operations can be conducted, being an added effect to the process (Bordalo-Machado, 2006).

In a downward progression comes the third factor, year. It was also most important in explaining the variability of the response, and this is result is as expected. Generally, the year factor is associated to annual variations in the recruitment, growth, fishing mortality or distribution patterns of the resource (Hilborn & Walters, 1992; Hinton & Maunder, 2003; Maunder & Punt, 2004; Bernasconi *et al.,* 2015). Thus, annual variations of catch rate are contingent of any of these variables, and ought to be reflected in explaining the year factor.

Hence, in this study, annual fluctuations of *Aphanopus spp.* LPUE estimated by the model are influenced by several variables that, overall, have medium to long-term effects on the amount of fish captured. The distribution pattern of this species may be related to this. It is nowadays a growing consensus that this species undertakes a large scale clockwise migration throughout the NE Atlantic, in which the northern areas of the distribution stretch all the way up towards Iceland, and the southern areas of the distribution locates in Madeira, Canary Islands and NW coast of Africa (*e.g.* Nakamura & Parin, 1993; Magnússon & Magnússon, 1995; Morales-Nin & Sena-Carvalho, 1996; Pajuelo *et al.,* 2008; Perera, 2008; Delgado *et al.,* 2013; Farias *et al.,* 2013; Santos *et al.,* 2013a,b). It is believed that this migration occurs for feeding and reproduction purposes, since the southern areas are the only ones where it occurs (Bordalo-Machado *et al.,* 2001; Figueiredo *et al.,* 2003; Neves *et al.,* 2009; Santos *et al.,* 2013). Thus, annual fluctuations are one of the results of such behaviour, and not only associated to natural changes of biomass.

Another variable affecting annual variations of *Aphanopus spp.* could be related to fishing efforts. Landings have been gradually decreasing, from approx. 3000 tonnes in 2008 to approx. 1900 tonnes in 2014 and 2015, though not accompanied by a reduction in effort [(number of vessels may have decreased from 34 in 2008 to 23 in 2015, but number of hooks deployed have remained stable (~15 million hooks), the number of fishing operations have risen slightly, and days at sea have also risen)]. A discussion can arise here regarding the performances of catch and effort. One reasonable argument could be that because of reducing catches, fishermen might have reservations on going out to sea. But, the reverse is as just or even more likely. What generally happens, and we can observe the numbers, is that fishermen facing lower catches, risk more, so they launch more gear, remain at sea more time, and so forth, to compensate those low catches. So, in an exploited resource where catches have been decreasing and effort has not decreased in the same proportion, it is somewhat logic to reach the conclusion that abundance may be lower than anticipated.

This annual fluctuation could also be the results of a new fleet strategy targeting *Aphanopus spp.*, but responding to the situation described above. Recently, the fleet has started to move northward, into the Azores EEZ and southward off Canary Islands (*Appendix B.3*; Bordalo-Machado *et al.*, 2009). Although more effort has to be made to move to such distant locations, captures may not compensate, or they do compensate, and fishermen return port with more fish than if they had stayed off Madeira. So, the resulting fluctuation would have been due to different fleet strategies related to fish abundance being lower closer to Madeira, but greater in other latitudes.

Therefore, it is expected that the year factor has such an impact in the model since variables like distribution, fleet strategy and reproduction all affect the availability of fish on an annual scale.

Considering another unit of effort that greatly contributed in the explicatory power of the model was days at sea. Basically described as the number of days spent at sea, it is also another variable where a logic explanation exists. The more basic analysis relates to its sheer nature, since more time spent at sea, the greater will be the amount of fish caught, and thus profits, although, there are some twists and turns about this raw analysis. For instance, if the fishery has gone sour, for whatever reason (*e.g.* illness of some crew member, engine failure, haul winch malfunction, rough weather, and many others), no matter the number of days a vessel spends at sea, it may possibly not matter because catch will not increase. In these cases, perhaps the best option is to return port and cut losses.

Another perspective can be related to the area covered. Since more days at sea mean basically more distance covered, the area effect might be associated with this variable. Some fishermen explore several areas, before exploring one that might meet expectations of large quantities of fish. The gear is deployed, the area is covered, and the process may start again in another area. Greater number of days spent at sea ensures that this procedure occurs more often, hence increasing the chances of finding areas where fish is more abundant (for this or that reason).

Other examples can be given, and no rule of thumb exists for any sort of analysis. Many days spent at sea may still signify very few catches, since it can be affected by so many factors (*e.g.* rough weather), and the permanence at sea might just be to continue to fish until bad luck runs out (as fisherman like to call it) and total catch increases. If catches do not improve, the number of days at sea will still be substantial but catches not. On the contrary, few days at sea may well mean lots of catches. For instance, leaving port, spending a couple of hours moving towards a fishing bank, hoisting the gear in an area where catches were very good the previous time the vessel was there, and finding nothing, can be very disappointing. If, driven by frustration, the skipper decides to leave the area (after deploying the gear) and explore another, closer to port, for instance a couple of hours away, and hoists the equipment (previously set up) and finds huge quantities of fish. The cargo hold is filled very quickly and the vessel returns port after few days at sea, in time to leave again, driven by a very satisfactory fishery.

Thus, the days at sea variable might be seen somewhat similar to the Gaussian curve, where few days may mean few catches, many days may mean lots of catches, but the contrary may as well happen, in which few days may mean lots of catches, and many days may mean few catches, being variant contingent on several variables, which cannot be foreseen in advance. In succinct, although a logic approach with very good reasoning may infer that more days at sea signify more catches, some deviations from this general notion may occur. So, the argument of more days at sea suggesting increased catches should be analysed carefully.

Regarding another vessel characteristic, the engine power, other studies in the field also analysed this variable in explaining LPUE variability. Bordalo-Machado & Figueiredo (2009) came to the conclusion that POW was significant but caused very little change in the deviance explained when the number of hooks was used as nominal effort. The same applies to this study, where nominal LPUE (kg/1000 hooks) is the response.

Considering the variable itself, the engine power, for obvious reasons, impacts the state of the fishery. Powerful engines enable the exploitation of a greater number of fishing areas further from port, granting the possibility to increase the chances of success, especially if success means venturing further away from the island. Also, a more powerful engine enables more equipment and crew to be carried than less powerful engines. Hence, engine power confers greater autonomy for fishers, so they can target this or that area without concerns such as if they will be able to reach that area, not being afraid of over-extending their capability of remaining longer at sea and also their deadlines.

The month factor also entered in adding explicatory power to the model. The month factor is usually related to changes of the stock abundance throughout the year, due to migrations, prey availability, spawning aggregations, and others (Bernasconi *et al.*, 2015). In this case, the month factor did not have a great influence in explaining the landings rates.

As reported by Bordalo-Machado & Figueiredo (2009), there seems to be a seasonality in landing rates. Although this study focuses in this fishery off mainland Portugal, conclusions can be withdrawn from it and explain the month effect for this case. Landings have a tendency to increase in the last quarter and first quarter of each year. Since spawning occurs not only but also in Madeira, it is reasonable to think that fish aggregate in the southern areas of the distribution to reproduce. Thus, the increased concentration of individuals for spawning purposes makes captures and thus landings increase in Madeira in that period (Bordalo-Machado *et al.*, 2009), thus conferring the month variable a somewhat significant influence in the explicatory power of the model.

Moreover, another tool to explain the monthly variance, could be related to the timing of spawning. Since the species spawns only in a restricted period of the year (*e.g.* Bordalo-Machado *et al.*, 2001; Figueiredo *et al.*, 2003; Neves *et al.*, 2009; Delgado *et al.*, 2013; Santos *et al.*, 2013), it is expected that fish availability is not the same throughout the year. Thus the monthly impact in the *Aphanopus spp.* LPUE estimates are mostly related to the spatial dynamics of this species' reproduction rather than abundance.

Lastly, the variable soaking time was also a component of the variability of the response. Described as the time the gear remains immersed, it is generally important in explaining the amount of fish caught, although not corroborated by this study. The influence of this variable on catches behaves just like a normal curve distribution. There exists an amount of time considered optimum for the gear to be in place, which is usually between 24 – 48 h (average of 38 h; Bordalo-Machado & Figueiredo, 2009; Bordalo-Machado *et al.*, 2009). If the gear remains longer in place, the success of capture starts to diminish, mainly because two things happen: 1) the odour of the bait fades to a point where attraction is difficult (Bordalo-Machado & Figueiredo, 2009); 2) captured individuals remain stuck in the hooks, and the longer they remain there, the higher the chances of being attacked by other black scabbards, being hauled with teeth marks in the body. The latter argument comes from fishermen reports about *Aphanopus spp.* being retrieved bitten. Hence, soaking time can only be analysed in increasing the chances of capture if retrieval is made within that optimal time, under or above which, its contribution starts to decline, and less explanatory power is given to the model.

Ultimately, the model designed explain roughly a third of the variability of LPUE. It is however, lacking some explanatory power, since several variables were not included in the analysis, whether because they are not a part of the data (not collected) or because some violated the model assumptions.

Even though in the range of previously submitted models focusing on black scabbardfish [Bordalo-Machado & Figueiredo (2009) reported 45% and 25% of explicability for the two models produced in the mainland Portugal continental slope; Machete *et al.* (2011) reported 42% explicability in the Azores], this model explained a low percentage of the total variability of the response, meaning that other factors play a role and may still be unaccounted for.

Although not accounted for, several parameters and interactions could have been used to increase the explanatory power of the model and thus explain the variability of the response (possibly at a cost of overfitting). The most direct approach in this case would be to simply evoke that other units of effort could have been used to increase the explanatory power of the model. Units such as crew members, vessel holding capacity, age of the vessel, crew experience, and capacity to produce ice through their own ice production unit, are some of the variables that can possibly bestow greater explanatory power to the analysis. They are however, intrinsically intertwined.

The size of the crew, and more importantly, their experience, are generally important factors in augmenting the chances of catching more fish. It is commonly known that an experienced crew produce amazingly good results, by exhibiting an incredible smoothness in fishing operations, thus optimizing the whole process. In addition, the skipper plays a huge role in fulfilling expectations. A veteran skipper, whose tremendous experience comes in light of many years at sea (like many battle-hardened soldiers), knowing the ins and outs of the fishery assures greater returns. On the contrary, a ‘greenhorn skipper’ (fishermen designation of a rookie skipper) tends to be less proficient, due to low experience and knowledge on fishing areas. With that said, it is common to verify that in the same vessel, skippers and crew members share the same experience and have as many years at sea amongst each other, since these are characteristics that usually are found hand in hand with one another.

The problem with this unit of effort, is that in Madeira (not only since in mainland Portugal the situation is more or less the same), this fishery maintains its familiar nature, in which sometimes, the difference between one vessel and another might just be a better connection that a skipper has with a certain crew member. Since no contractual obligations exist between a vessel and a crew member, these often change with frequency, being thus very difficult tracking these changes in crew composition. As a consequence, the error associated with this variable is highly significant, and the usage of variables such as these might yield certain uncertainties and must be analysed cautiously.

Another variable associated to the vessels features that might have decisive impact on catch rate performance is the holding capacity. Described as the amount of cargo they can hold, vessels that can contain greater numbers of freshly caught fish are able to maintain themselves at sea for extended periods of time, since larger vessels take longer to fill than smaller vessels.

Also, closely related with this variable is the capability to produce their own ice. The deepwater fishery of in Madeira is small in numbers and in sheer magnitude. Vessels that carry out this activity are somewhat small (mean features in 2015 of 12.43 LOA, 19.95 GT and 134.03 POW) compared to other vessels targeting other fish resources. In result, the autonomy of these vessels is greatly compromised since venturing further away from port implies greater costs and most of all, on the ability to catch and effectively conserve fish long enough so that it is landed in perfectly good conditions. Since the Madeiran vessels do not have ice production units, they rely on ice produced at port, by official entities related to the DRP. Hence, catching and landing capacity are somewhat restrained by such dependency, which is why this variable would confer some degree of explanation on the performance of LPUE.

Some authors rely on another variable, namely the vessels' age. Although the age itself has almost no meaning whatsoever, it is when converging with other variables that it might provide some explanatory power. This variable can be closely related to the crew experience (Bordalo-Machado, 2009). It is usually a common knowledge in fisheries that older vessels have older crew members (can be associated with social bonds coming from the same social-economic background), which is advantageous since experienced crews usually offer great returns due to their ability to catch more fish in less time (related to speed at which they handle the equipment and all aspects of the fishery). Another argument may arise when new vessels enter the fleet, especially if those vessels are manned by experienced crews, coming from older vessels. This renewal would then tear down the previously stated argument. Thus, as shown previously, this is not a rule of thumbs, and common sense and prior knowledge on the fishery would at least let us believe that this variable would grant a greater degree of explicability to LPUE estimations, and presence in this data set would have been useful.

Other variables would provide alternative answers, and could go into deeper lengths in explaining the variability of LPUE. The spatial factor is another tool that if provided, could contribute significantly for the explanatory power of the model. Although the main areas where fishing occurs have been described (*Appendix B.3*) (STECF, 2014; Delgado *et al.*, 2016), accurate information of the fishing areas each time a vessel is actively fishing was not available for this study. Although it is shown in *Appendix B.3* the areas where fishing occurred, it was compiled through personal enquiries and log-books, but they are not a part of the PNRDP, and since the data used here is collected as an intrinsic part of the program, it was not available in this study. However, if it were, such information would have allowed to evaluate the overlap between the fleet and the distribution of *Aphanopus spp*. Also, by knowing precisely the area where fishing occurred, conclusions can be withdrawn from this since changing fishing patterns usually follow changing abundance tendencies.

The depth at which the longline is deployed is generally a factor to consider in any analysis, although in this case it might have not increased the explicability of the model. This is because the standard procedure, followed by fishermen across the fleet, is to deploy the longline at a depth of 1000 m, and the hooks are usually suspended from that line at a depth of 1200 m approx., since the line has an arch-like shape directed upwards, so it usually goes further down the water column. Thus introducing this variable, knowing beforehand that this procedure is followed by every vessel, would not increase the explicability of the model, since no variability exists between vessels in this particular aspect of the fishery.

Other factors might have been included in the analysis as part of the spatial scale. Depth is such a variable. Since *A. carbo* is a deepwater benthopelagic species that rises in the water column at night for feeding purposes (Delgado *et al.*, 2013), placing the longline at depths where it is more abundant (700 – 1300 m) is crucial in order to maximize captures. Hence, information related to the depth in which the gear was placed is probably another variable to consider for explaining the abundance of this species.

Environmental cues are another set of variables that if available, could provide better insight in estimation of abundance indexes and increase the accuracy of the model. It is generally known that the deep sea is characterized by high pressures, low temperatures, no light, different dissolved oxygen and salinity concentrations. These features hinder the metabolic rate process of fishes, as well as on predation stress, food availability, and amongst other processes (Merrett & Haedrich, 1997).

The type of bait is another variable where, if available, could have been used to add to the model. It has been shown that the preferred baits are orangeback squid (*Sthenoteuthis pteropus*), as reported by INIP (1984), but also squid (*Omnastrephes sp.*), horse mackerel (*Trachurus picturatus*) and chub mackerel (*Scomber colias*) (Bordalo-Machado & Figueiredo, 2009; Bordalo-Machado *et al.*, 2009; Santos *et al.*, 2013). Since the effects of different types of bait remain mathematically unknown (although the fishermen prefer the squids), this analysis with the bait type would have granted greater explicability to the model.

Abundance trends were calculated in this study through the performance of nominal vs. standardized LPUE. These exhibited similar behaviours, although standardized values are fairly lower than nominal values. Such relationship was expected, since several explanatory variables were abandoned, decreasing the abundance estimate, though approaching it to reality. The abundance of *Aphanopus spp.* showed marked inter-annual fluctuations, with years of higher abundances than others. The highest abundance was observed in 2012 and the lowest in 2013. Also, when plotting nominal LPUE vs. standardized LPUE in effort scales, the same behaviour was observed. These exhibit similar trends, with standardized LPUE significantly lower than nominal LPUE, although the tendency is to increase LPUE estimations as the effort increases as well.

Therefore, the overall analysis of LPUE performance in these past eight years indicates that the exploitation of *Aphanopus spp.* in Madeira appears to be steadily declining, substantiated by landings performance but also by the behaviour of the fleet, which adjusted to decreasing abundances in Madeiran waters, and now explore fishing areas further away from the island, mainly venturing north to the Azores and south to the Canary Islands (*Appendix B.3*) (Bordalo-Machado *et al.*, 2009; Delgado *et al.*, 2016).

The reasons why CPUE may not be proportional to abundance have been investigated by simulation (Gillis & Peterman, 1998), and through examination of empirical data (Rose & Leggett, 1991). The most common form of non-proportionality relates to hyperstability (*Appendix B.4*). This occurs when CPUE remains high while abundance declines (Hilborn & Walters, 1992). This can significantly underestimate true declines in a population. As an example, this can occur when fishermen target new fishing areas where fish is concentrated (higher abundance), but catches (thus landings) remain constant, not reflecting the overall state of the population. Consequently, assuming that the LPUE index reflects the true trend in population, can result in underestimates of exploitation rate and total population decline (Hilborn & Walters, 1992; Hoof & Salz, 2001; STECF, 2014).

Conversely, the opposite may happen as well. Hyperdepletion describes a situation where catch rate declines faster than population biomass (*Appendix B.4*) (Hilborn & Walters, 1992). This can occur when fishing is concentrated in a subset of the population, while significant subsets of the population remain unaccounted for in the index rate. This basically means that abundance estimates are underestimating the overall performance of abundance since not all areas of exploitation are covered. Therefore, estimates such as this should not be overly interpreted unless additional information is available from other areas (Hilborn & Walters, 1992; Hoof & Salz, 2001; STECF, 2014).

In the case of the black scabbard fishery in Madeira, an hyperstability situation may well explain the scenario in the archipelago. As shown in previous paragraphs, total landings have roughly stabilised around 2000 tonnes throughout the last decade. Although this may happen, the overall pattern of the fleet behaviour should be analysed if abundance estimates are to made accurately as possible.

The black scabbard fleet based in Madeira has been exploiting areas further away from the island in the last decade. In the fishermen's perspective, fishing in areas further from port implicate greater costs, not only of fuel but also of supplies for the crew and most importantly, it involves conserving the fish a little while longer before selling it at port, which can compromise the quality of the fish and the overall profit. So it is not in the fishermen best interest to explore areas further away from the island, unless fish abundance is decreasing. In this case, the fishermen in order to compensate lower catches, venture further away, exploiting other areas while hopping that investment compensates the greater risk.

Thus, analysing *Appendix B.3*, it is possible to clearly visualize the exploitation trends of the fleet based in Madeira. Since they have recently started to exploit the southern areas close to the Canary Islands, and northern areas close to the Azores, the only rational explanation is that the abundance in Madeiran waters is lower than in those areas (Delgado *et al.*, 2016). Considering the previous paragraph, where fishermen only explore more distant areas if it's absolutely necessary, and also the recent agreements between Madeira, the Azores and Canary Islands governments for allowing Madeiran fleet to enter the waters administrated by these regions (Delgado *et al.*, 2016), one possible conclusion, and probably the strongest one, is that the stock has been decreasing in Madeiran traditional fishing grounds, but this decline has been compensated by catches in other fishing grounds located outside Madeira EEZ, masking the overall tendency of abundance estimates.

A very interesting question can be brought up to this discussion, as stated by Delgado *et al.* (2016). Considering that this species undertakes a large scale clockwise migration throughout the NE Atlantic (*e.g.* Nakamura & Parin, 1993; Magnússon & Magnússon, 1995; Morales-Nin & Sena-Carvalho, 1996; Pajuelo *et al.,* 2008; Perera, 2008; Delgado *et al.,* 2013; Farias *et al.,* 2013; Santos *et al.,* 2013a,b), it makes sense that a discussion about exploitation measures should be done converging all the areas where it is present. As such, northern areas such as in Bay of Biscay, West of the British Isles and Hatton Bank, and in Icelandic waters, should all be included in the discussion of management of the resource with its southern areas of the distribution, Madeira, Canary Islands and NW coast of Africa, where spawning occurs. It is only by implementing precautionary measures in all of these areas that ultimately the fishery can continue to profit from this exploitation. So, no matter how good the recruitment is in southern areas, if no management measures are introduced, the stock may continue to decrease, affecting as a consequence, the overall abundance of the species in the NE Atlantic.

Although converging efforts is paramount for the sustainability of this fishery, the latest ICES report of June (ICES, 2016), discussed the continuation of the exploitation rates, with no reinforcements of the management strategies. As stated: “the exploitation of the stock is considered to be very low and therefore no additional precautionary buffer was applied. Therefore, the advice for this fishery in 2017 and 2018 is the same as the advice for 2015–2016, (…)”. Such conclusions are only based in ICES areas, not taking into consideration the FAO CECAF 34.1.2 area of Madeira. Thus, in this perspective and following the conclusions of Delgado *et al.* (2016), it is advisable to, before establishing such quotas, to do a comprehensive study, where all areas are approached and managing options are devised for the entire stock, not for subsets.

For scientists and decision makers, imposing management measures in such case is a double-edged sword. Although continuation of the fishery is something fundamental, mainly because many people are employed by this activity, the fact remains that restraining measures must be considered so that this activity is to endure.

This study covered the Madeira fishing fleet targeting *Aphanopus spp.* The data used revealed to be slightly skewed, which is more than understandable considering its commercial nature. Nevertheless, all things considered, the model proved to be adequate in describing the features of the fishery in Madeira, and conclusions made out from those calculations reveal, to some extent, the true abundance pattern of *Aphanopus spp.* in Madeira EEZ.

For future reference, the results obtained in this study can be improved on several levels, especially if data with longer time series is available, if more explanatory variables are available (*e.g.* bait type, environmental characteristics that affect the fishery, fleet strategy information, other variables related to effort, and others), and if efforts are made to reduce the skewness of the information gathered, so that an overall picture of the fishery of this resource in Madeira is to be made.

CHAPTER 4

Final Considerations

- In this study, the two primary goals were to continue to gather information on *Aphanopus carbo* biology in Madeiran waters, and to present as best as possible, the state of the fishery of *Aphanopus spp.* (not only *A. carbo* but also *A. intermedius* since both are not distinguished at landings) in FAO CECAF 34.1.2 area, which includes the Madeira Archipelago.

- In order to achieve the first goal, *A. carbo* individuals were analysed. These were landed in Madeira Archipelago ports, where a comprehensive analysis of its biology was performed. It included an analysis of the population structure in terms of length, weight, also covering sex ratios, reproductive cycle, condition factor, L_{50s} and WLRs and LLRs. The other objective comprised of analysing landing trends of *Aphanopus spp.*, the evolution of the fishing fleet, and estimating, as precise as possible, an abundance estimate. Explanatory variables deemed significant and meaningful were included and the model explained the best as possible the status of the deepwater fishery targeting *Aphanopus spp*. Standardized estimates were plotted against nominal estimates and conclusions were withdrawn from it.

- The overall conclusions in terms of the biology of *A. carbo* are: 1) this resource attains its biggest length and weight in Madeiran waters, closely related to the nature of its life cycle; 2) as expected, it is prevalent the presence of mature individuals in Madera waters, since it is widely known as a spawning ground for this species; 3) the reproductive cycle, through the analysis of GSI and HSI, shows clearly that reproduction occurs in the last quarter of the year; 4) individuals attain their best body condition in the last quarter of the year, corroborating the previous statement; 5) L_{50s} did not deviate from previous studies and shows that its values are greatest in the southern areas for the distribution; 6) WLRs exhibit isometric and allometric growth patterns and LLRs exhibit only allometric, meaning that they grow evenly between length and weight but not in body length and caudal length;

- The overall conclusions in terms of *Aphanopus spp.* landing trends and standardization procedure: 1) total landings have decreased significantly over the course of the period in question, with an average of 2000 tonnes/year; 2) the fleet has shrunk in the past years; 3) effort has not decreased alongside with the fleet size; 4) standardized LPUE was significantly lower than nominal LPUE; 5) GT, fishing operations and year were the predictors that greatly contributed to the model explicability; 6) an hyperstability situation appears to explain the status of the deepwater fishery in the traditional fishing grounds; 7) catches have been compensated by vessels venturing further from the islands, into Canaries and the Azores, masking the true performance of the catches in the traditional fishing grounds; 8) additional precautionary management measures are required to further this fishery, covering all areas of its distribution, northern and southern.

- This study presented a comprehensive analysis on several biological characters and population structure in this part of the NE Atlantic, and also new information regarding abundance estimates of *Aphanopus spp.*

- This study has shown that *A. carbo* is intrinsically connected to the Madeira Archipelago, being fundamental to the livelihoods of many inhabitants of the islands.

- The management of this resource can be described as bicephalous. Two areas of management programmes are covered, the ICES and CECAF areas and, given the widely accepted hypothesis of a clock-wise migration throughout the NE Atlantic, both entities need to converge efforts to increase awareness in protecting this resource and if necessary, to reduce quotas to endure this activity, or to introduce a temporary closed season, to allow individuals to attain sexual maturity, thus preventing the harvest of immature individuals.

- As a future endeavour, an interesting approach would be to analyse the egg and larval stages of this resource, improving our knowledge on the population structure, their behaviour in those stages and possibly the migration pattern and time of migration.

- It would be also very important to understand how this consequence of lower abundance in traditional fishing grounds in Madeiran EEZ affects the other areas of the distribution, and such analysis merits further investigation.

References

Akaike, H. (1973). Information theory and an extension of the maximum likelihood principle. *Proceedings of the* 2^{nd} *International Symposium on Information Theory*. Akademiai Kiado, Budapeste, 268-281.

Ali, A., Dahanukar, N. and Raghavan, R. (2013). Length-weight and length-length relationship of three species of snakehead fish, *Channa diplogramma*, *C. marulius* and *C. striata* from the riverine reaches of lake Vembanad, Kerala, India. *Journal of Threatened Taxa*, 5(13): 4769-4773.

Allain, V., Biseau, A., Kergoat, B. (2003). Preliminary estimates of French deepwater fishery discards in the Northeast Atlantic Ocean. *Fisheries Research*, 60: 185–192.

Ambar, I. and Howe, M. R. (1979). Observation of the Mediterranean outflow. I. Mixing in the Mediterranean outflow. *Deep-Sea Research*, 26A: 535-554.

Anon. (1999a). Environment and Biology of deep sea water species Aphanopus carbo in the NE Atlantic: basis for its management (BASBLACK). Individual interim report for the period 01-05-1998 to 30-04-1999: 10 pp. + Annex.

Anon. (1999b). Environment and Biology of deep sea water species Aphanopus carbo in the NE Atlantic: basis for its management (BASBLACK). Individual interim report for the period 01-04-1999 to 30-12-1999 + Annex+ tables.

Anon. (2000). Final Report of the EU study project 97/0084 Environment and biology of deep water species Aphanopus carbo in the NE Atlantic: basis for its management (BASBLACK). In DGXIV European commission, p. 94 pp.

Bailey, R. (1982). The population biology of blue whiting in the North Atlantic. *Advances in Marine Biology*, 19: 257-355.

Barrón, E., Rivas-Carballo, R., Postigo-Mijarra, J. M., Alcalde-Olivares, C., Vieira, M., Castro, L., Pais, J., Valle-Hernández, M. (2010). The Cenozoic vegetation of the Iberian Peninsula: A synthesis. *Review of Palaeobotany and Palynology*, 162: 382-402.

Bentley, N., Kendrick, T. H., Starr, J. P., Breen, P. A. (2011). Influence plots and metrics: tools for better understanding fisheries catch-per-unit-effort standardizations. *ICES Journal of Marine Science*. 5pp. doi:10.1093/icesjms/fsr174.

Bernasconi, J. F., Perier, M. R., Giácomo, E. E. D. (2015). Standardized catch rate of cockfish, Callorhinchus callorynchus, in a bottom trawl fishery of Patagonia: Is it possible its use as a predictor of abundance trend? *Brazilian Journal of Oceanography*, 63(2): 147-160.

Biscoito, M., Delgado, J., González, J. A., Stefanni, S., Tuset, V. M., Isidro, E., Garcia-Mederos, A. Carvalho, D. (2011). Morphological identification of two sympatric species of Trichiuridae, *Aphanopus carbo* and *A. intermedius*, in NE Atlantic. *Cybium* 35: 19-32.

Bordalo-Machado, P., Figueiredo, I., Reis, S., Sena-Carvalho, D., Blasdale, T., Newton, A., Gordo, L. S. (2001). New Findings on the Reproductive Biology of the Black Scabbardfish (*Aphanopus carbo* Lowe, 1839) in the NE Atlantic. *Deep-sea Fisheries Symposium*, NAFO SCR Doc. 01/89.

Bordalo-Machado, P. (2006). Fishing Effort Analysis and Its Potential to Evaluate Stock Size. *Reviews in Fisheries Science*, 14: 369-393.

Bordalo-Machado, P. and Figueiredo, I. (2009). The fishery for black scabbardfish (*Aphanopus carbo* Lowe, 1839) in the Portuguese continental slope. *Reviews in Fish Biology and Fisheries*, 19: 49-67.

Bordalo-Machado, P., Fernandes, A. C., Figueiredo, I., Moura, O., Reis, S., Pestana, G., Gordo, L. S. (2009). The black scabbardfish (*Aphanopus carbo* Lowe, 1839) fisheries from the Portuguese mainland and Madeira Island. *Scientia Marina*, 73S2: 63-76.

Borets, L. A. (1986). Ichthyofauna of the Emperor Seamount Chain and Hawaiian Submarine Ridge. *Voprosy ikhtiologii*, 26: 208–220.

Borges, P. A. V., Abreu, C., Aguiar, A. M. F., Carvalho, P., Jardim, R., Melo, I., Oliveira, P., Sérgio, C., Serrano, A. R. M. & Vieira, P. (2008). A list of the terrestrial fungi, flora and fauna of Madeira and Selvagens Archipelagos. Direção Regional do Ambiente da Madeira and Universidade dos Açores. Funchal and Angra do Heroísmo, 440 pp.

Caldeira, R. and Lekou, S. (2000). *Madeira, Um Oásis no Atlântico. Uma Introdução ao Estudos Oceanográficos no Arquipélago da Madeira*. Funchal, Madeira: Direção Regional de Formação Profissional. 106p.

Caldeira, R. M. A., Groom, S., Miller, P., Pilgrim, D., Nezlin, N. P. (2002). Sea-surface signatures of the island mass effect phenomena around Madeira Island, Northeast Atlantic. *Remote Sensing of Environment*, (80): 336-360.

Campbell, R. A. (2004). CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. *Fisheries Research*, 70: 209-227.

Capelo, J., Menezes de Sequeira, M., Jardim, R., Mesquita, S. (2007). Biologia e ecologia das florestas das ilhas - Madeira. Árvores e Florestas de Portugal: Açores e Madeira - A Floresta das Ilhas (ed. by J. Silva), pp. 81-134. Público, Comunicação Social SA, Fundação Luso Americana para o Desenvolvimento e Liga para a Protecção da Natureza.

Carvalho, J. A. (2001). Contribuição para o estudo da diferenciação populacional do peixe espada-preto (*Aphanopus carbo*, Lowe, 1839) na região sul do Nordeste Atlântico. *Estágio Profissionalizante*, FCUL, Lisboa: 46 pp + Anexos.

Carvalho, F., Ahrens, R., Murie, D., Ponciano, J. M., Aires-da-Silva, A., Maunder, M., Hazin, F. (2014). Incorporating specific change points in catchability in fisheries stock assessment models: An alternative approach applied to the blue shark (*Prionace glauca*) stock in the south Atlantic Ocean. *Fisheries Research*, http://dx.doi.org/10.1016/j.fishres.2014.01.022

Clarke T. A. and Wagner, P. J. (1976). Vertical distribution and other aspects of the ecology of certain mesopelagic fishes taken near Hawaii. *Fishery Bulletin*, 74: 635-645.

Crespo, L. C., Silva, I., Borges, P. A. V., Cardoso, P. (2014). Assessing the conservation status of the strict endemic Desertas wolfspider, *Hogna ingens* (Araneae, Lycosidae). *Journal for Nature Conservation*, 22(6): 516-524.

Dadzie, S. and Wangila, B. C. C. (1980). Reproductive biology, length-weight relationship and relative condition of pond raised *Tilapia zilli* (Gervais). *Journal of Fish Biology*, 17: 243-253.

Delgado, J. M. M. H. (2007). Ictiofauna Demersal das Zonas Sublitoral e Batial Superior do Arquipélago da Madeira. Um Estudo Biológico e Ecológico. Tese de Mestrado, Universidade da Madeira, Funchal, Portugal. 169p.

Delgado, J., Reis S., González, J. A., Isidro, E., Biscoito, M., Freitas, M., Tuset, V. M. (2013). Reproduction and growth of *Aphanopus carbo* and *A. intermedius* (Teleostei: Trichiuridae) in the northeastern Atlantic. *Journal of Applied Ichthyology*, 29: 1-7.

Delgado, J., Amorim, A., Gouveia, L., Gouveia, N. (2016). Trends in the Spatial Distribution of the Deep Sea Fishery of the Madeira Archipelago (North-Eastern Atlantic). XIX Iberian Symposium on Marine Biology. Studies (SIBEM XIX), Porto, Portugal.

Dorcas, I. K. and Solomon R. J. (2014). Calculation of liver function test in *Clarias Gariepinus* collected from three commercial fish ponds. *Nature and Science*, 12(10): 107-123.

DREM (2015a). Série Retrospetiva das Estatísticas de Agricultura e Pescas da Região Autónoma da Madeira (1976-2014). Direção Regional de Estatística da Madeira, Funchal. 40p.

DREM (2015b). Estatísticas da Agricultura e Pesca da Região Autónoma da Madeira 2014. Direção Regional de Estatística da Madeira, Funchal. 70p.

Ech-chakrouni, S. (2004). Géochronologie Et Paléomagnetisme de l'île de Madère et des îles Desertas. PhD Thesis – Vrije Universiteit Brussel, 232 pp.

Ehrich, S. (1983). On the occurrence of some fish species at the slopes of the Rockall Trough. *Archives of Fisheries*, 33: 105-150.

Ellett, D. J., Edwards, A., Bowers, R. (1986). The hydrography of the Rockall Channel – an overview. *Proceedings of the Royal Society of Edinburgh*, 88B: 61-81.

Ellis, P. D. (2010). The Essential Guide to Effect Sizes: An Introduction to Statistical Power, Meta-Analysis and the Interpretation of Research Results. United Kingdom: Cambridge University Press.

FAO. (1998). Guidelines for the routine collection of capture fishery data. *FAO Fisheries Technical Paper*. No. 382. Rome, 113p.

Farias, I., Morales-Nin, B., Lorance, P., Figueiredo, I. (2013). Black scabbardfish, *Aphanopus carbo*, in the Northeast Atlantic: distribution and hypothetical migratory cycle. *Aquatic Living Resources*, 26(4): 333-342.

Farias, I., Figueiredo, I., Janeiro, A. I., Bandarra, N. M., Batista, I., Morales-Nin, B. (2014). Reproductive and feeding spatial dynamics of the black scabbardfish, Aphanopus carbo Lowe, 1839, in NE Atlantic inferred from fatty acid and stable isotope analyses. *Deep-Sea Research I*, http://dx.doi.org/10.1016/j.dsr.2014.04.010.

Ferreira, M. P. (1985). Evolução geocronológica e paleomagnética das ilhas do Arquipélago da Madeira – uma síntese. Memórias e Notícias. *Publicações do Museu e Laboratório Mineralógico e Geológico da Universidade de Coimbra*, 99: 213-218.

Ferreira, M. P., Macedo, C. R., Ferreira, J. F. (1988). K-Ar geochronology in the Selvagens, Porto Santo and Madeira Islands (Eastern Central Atlantic): A 30 m.y. spectrum of submarine and subaerial volcanism. *Lunar Planetary Institute Abstracts*, 19: 325-326.

Ferreira, M. P. and Neiva, J. C. (1996). Carta Geológica de Portugal, Folha de Porto Santo à escala 1:25 000, Universidade de Coimbra/Instituto Geológico e Mineiro.

Finley, C. (2009). The Social Construction of Fishing, 1949. *Ecology and Society*, 14(1): 6.

Figueiredo, I., Bordalo-Machado, P., Reis, S., Sena-Carvalho, D., Blasdale, T., Newton, A., Gordo, L. S. (2003). Observations on the reproductive cycle of the black scabbardfish (*Aphanopus carbo* Lowe, 1839) in the NE Atlantic. *ICES Journal of Marine Science*, 60: 774–779.

Fitch J. E., Gotshall, D. W. (1972). First record of the black scabbardfish, *Aphanopus carbo*, from the Pacific Ocean with notes on other Californian trichiurid fishes. *Bulletin of the Southern California Academy of Sciences*, 71: 12-18.

Flores, A., Wiff, R., Díaz, E. (2014). Using the gonadosomatic index to estimate the maturity ogive: application to Chilean hake (*Merluccius gayi gayi*). *ICES Journal of Marine Science*, doi:10.1093/icesjms/fsu155.

Fonteneau, A. (1998). Introduction aux problemes des relations Thons-Environment dans l'Atlantique. *ICCAT, 25 Tuna Symposium, vol. L*(1): 275-317.

Frank, K. T., Petrie, B., Fisher, J. A. D., Leggett, W. C. (2011). Transient dynamics of an altered large marine ecosystem. *Nature*, 477: 86-88.

Froese R. (2006). Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations. *Journal of Applied Ichthyology*, 22(4): 241-253.

Froese, R., Tsikliras, A. C., Stergiou, K. I. (2011). Editorial note on weight-length relations of fishes. *Acta Ichthyologica et Piscatoria*, 41(4): 261-263.

Geldmacher, J., Bogaard, P. V. D., Hoernle, K., Schmincke, H. (2000). The ^{40}Ar/^{39}Ar age dating of the Madeira Archipelago and hotspot track (eastern North Atlantic). *Geochemistry, Geophysics, Geosystems*, 1: 1-26.

Geldmacher, J., Hoernle, K., Klügel, A., Bogaard, P. v. d., Wombacher, F., Berning, B. (2006). Origin and geochemical evolution of the Madeira-Tore Rise (eastern North Atlantic). *Journal of Geophysical Research*, 111: B09206.

Gillis, D. M., and Peterman, R. M. (1998). Implications of interference among fishing vessels and the ideal free distribution to the interpretation of CPUE. *Canadian Journal of Fisheries and Aquatic Sciences*, 55: 37-46.

Gomiero, L. M., Villares Junior, G. A., Braga, F. M. S. (2010). Length-weight relationship and condition factor for *Oligosarcus hepsetus* (Cuvier, 1829) in Serra do Mar State Park – Santa Virgínia Unit, Atlantic Forest, São Paulo, Brazil. *Biota Neotropica*, 10(1): 101-105.

Gonçalves, A. B. and Nunes, R. S. (Eds). (1990). *Ilhas de Zargo*. Adenda. Funchal, Madeira. 217-262 pp.

Gonçalves, J. M. S., Bentes, L., Lino, P. G., Ribeiro, J., Canário, A. V. M., Erzini, K. (1997). Weight-length relationships for selected fish species of the small-scale demersal fisheries of the south and south-west coast of Portugal. *Fisheries Research*, 30: 253-256.

Gorbunova, N. N. (1977). Larvae of some trichiuroid fishes (Pisces, Trichiuroidae: Gempylidae, Trichiuridae. *Trudy IOAN SSSR.*, 109: 133–148.

Gordo, L. S., Carvalho, D. S., Figueiredo, I., Reis, S., Machado, P. B., Newton, A., Gordon, J. (2000). The sexual maturity scale of black scabbardfish: A macro- and microscopic approach. *Celta Editora*, Oeiras, 35p.

Gordo, L. S. (2009). Black scabbardfish (*Aphanopus carbo* Lowe, 1839) in the southern Northeast Atlantic: considerations on its fishery. *Scientia Marina*, 73S2: 11-16.

Gordo, L. S., Baptista, I., Carvalho, L., Costa, V., Cruz, C., Eiras, J. C., Farias, I., Figueiredo, I., Lourenço, H., Bordalo-Machado, P., Neves, A., Nunes, M. L., Reis, S., Santos, M. J., Saraiva, A., Vieira, A. R. (2009). Stock structure of black scabbardfish (*Aphanopus carbo* Lowe, 1839) in the southern northeast Atlantic. *Scientia Marina*, 73S2: 89-101.

Haddon, M. (2001). Modelling and Quantitative Methods in Fisheries. Chapman & Hall/CRC, A RC Press Company. Boca Raton, Florida. 406p.

Haedrich, R. L., Merrett, N. R., O'Dea, N. R. (2001). Can ecological knowledge catch up with deep-water fishing? A North Atlantic perspective. *Fisheries Research*, 51: 113-122.

Hale, R. (2009). Interacção da foca-monge (*Monachus monachus*) com as diversas artes de pesca da Região Autónoma da Madeira. Dissertação submetida à Faculdade de Ciências da Universidade do Porto para obtenção do grau de Mestre em Biologia. 111p.

Hamilton, W. D. (1967). "Extraordinary sex ratios". *Science*, 156(3774): 477-488.

Hardin, G. (1968). "The Tragedy of the Commons". *Science*, 162(3859): 1243-1248.

Hauke, J. and Kossowski, T. (2011). Comparison of values of Pearson's and Spearman's correlation coefficients on the same sets of data. *Quaestiones Geographicae*, 30(2): 87-93.

Hilborn, R. and Walters, C. J. (1992). Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman & Hall, New York, 570 pp.

Hinton, M. G., and Maunder, M. N. (2003). Methods for standardizing CPUE and how to select among them. Inter-American Tropical Tuna Commission. SCTB16 Working Paper, 8604, La Jolla, California 92037-1508 USA.

Hoof, L. V., and Salz, P. (2001). Applying CPUE as management tool. Agricultural Economics Research Institute LEI Fisheries Division, The Hague, Netherlands. 9pp.

Hossain, M. Y., Ahmed, Z. F., Leunda, P. M., Islam, A. K. M. R., Jasmine, S., Oscoz, J., Miranda, R., Ohtomi, J. (2006). Length–weight and length–length relationships of some small indigenous fish species from the Mathabhanga River, southwestern Bangladesh. *Journal of Applied Ichthyology*, 22: 301-303.

Howe, K. M., Steine, D. L., Bond, C. E. (1980). First records off Oregon of the pelagic fishes *Paralepis atlantica*, *Gonostoma atlanticum* and *Aphanopus carbo*, with notes on the anatomy of *Aphanopus carbo*. *Fishery Bulletin*, 77: 700–703.

Hoyle, S. D., Langley, A. D., Campbell, R. A. (2014). Recommended approaches for standardizing CPUE data from pelagic fisheries. WCPFC-SC10-2014/ SA-IP-10. Majuro, Republic of the Marshall Islands. 21p.

ICES (2002). Report of the Working Group on the Biology and Assessment of Deep-Sea Fisheries Resources. ICES CM 2002/ACFM, 25.

ICES (2014). Black scabbardfish stock annex: Stock specific documentation of standard assessment procedures used by ICES. ICES WKDEEP REPORT, revised by WKDEEP-2014 / Ivone Figueiredo, 42-61.

ICES (2016). ICES Advice on fishing opportunities, catch, and effort. Northeast Atlantic Ecoregion. ICES Advice, Book 9. 9p.

INE (2015). Estatísticas da Pesca 2015. Instituto Nacional de Estatística, I. P. Lisboa, Portugal. 144p.

INIP (1984). Programa de apoio às pescas na Madeira – IV, Cruzeiro de reconhecimento de Pesca e Oceanografia 020390582. *Relatório INIP*, Lisboa (25), 125p.

Jørgensen, C., Ernande, B., Øyvind, F., Dieckmann, U. (2006). The logic of skipped spawning in fish. *Canadian Journal of Fisheries and Aquatic Sciences*, 63: 200-211.

Kelly, C. J., Connolly, P. L., Clarke, M. W. (1998). The deep waters fisheries of the Rockall trough; some insights gleaned from Irish survey data. ICES CM 1998/O:40.

Keskar, A., Kumkar, P., Paingankar, M. S., Padhye, A., Dahanukar, N. (2015). Length-weight and length-length relationships of seven loach species (Teleostei: Cypriniformes) from five localities in northern Western Ghats, India. *Journal of Threatened Taxa*, 7(15): 8205–8220.

King, M. (1995). Fisheries Biology, Assessment and Management. Fishing News Books. 1st edition. Oxford, 34p.

Kokokiris, L., Stamoulis, A., Monokrousos, N., Doulgeraki, S. (2014). Oocytes development, maturity classification, maturity size and spawning season of the red mullet (*Mullus barbatus barbatus* Linnaeus, 1758). *Journal of Applied Ichthyology,* 30: 20-27.

Lauth, R. R. (1997). The 1995 Pacific West coast upper continental slope trawl survey of groundfish resources off southern Oregon and northern California: Estimates of distribution, abundance, and length composition. US Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-80.

Le Cren E. D. (1951). The length–weight relationship and seasonal cycle in gonad weight and condition in the perch (*Perca fluviatilis*). *Journal of Animal Ecology*, 20(2): 201-219.

Leite, A. M. (1988). The deep-sea fishery of the black scabbard fish *Aphanopus carbo* Lowe, 1839 in Madeira Island waters. *Proceedings of the 1988 World Symposium on Fishing Gear and Fishing Vessel Design*, St John’s, Newfoundland, Canada, 240-243.

Lloris, D., Rucabado, J., Figueroa, H. (1991). The Biogeography of the Macaronesian Ichthyofauna (The Azores, Madeira, The Canary Islands, Cape Verde and the African Enclave). *Boletim do Museu Municipal do Funchal*, 43(234): 191-241.

Longmore, C., Trueman, C., Neat, F., O'Gorman, E. J., Milton, J. A., Mariani, S. (2011). Otolith geochemistry indicates life-long spatial population structuring in a deep-sea fish, *Corypahenoides rupestris*. *Marine Ecology Progress Series*, 435: 209-224.

Lowerre-Barbieri, S. K., Henderson, N., Llopiz, J., Walters, S., Bickford, J., Muller, R. (2009). Defining a spawning population (spotted seatrout *Cynoscion nebulosus*) over temporal, spatial, and demographic scales. *Marine Ecology Progress Series*, 394: 231-245.

Machete, M., Morato, T., Menezes, G. (2011). Experimental fisheries for black scabbardfish (*Aphanopus carbo*) in the Azores, Northeast Atlantic. *ICES Journal of Marine Science*, 68(2): 302-308.

Magnússon J. V. and Magnússon J. (1995). The distribution, relative abundance, and the biology of the deep-sea fishes of the Icelandic slope and Reykjanes Ridge. In: Hopper A.G. (Ed.) Deepwater Fisheries on the North Atlantic Oceanic Slope, Kluwer Academic, 161-199.

Magnússon, J., Magnússon J. V., Jakobsdóttir, K. (2000). Icelandic contributions to the deep water research project EC FAIR PROJECT CT 95-0655, 1996-1999. *Hafrannsó Knastofnun Fjölrit*, 76: 164pp.

Mai, D. H. (1989). Development and regional differentiation of the European vegetation during the Tertiary. *Plant Systematics and Evolution*, 162: 79-91.

Malthus, T. R. (1798). An Essay on the Principle of Population. First printed for J. Johnson, in St. Paul's Church-Yard, London. Electronic Scholarly Publishing Project, 1998. 125p.

Marques, C. A. G. (2013). Paleobotânica da Ilha da Madeira: Inventário e Revisão da Macroflora Fóssil de São Jorge e Porto da Cruz. Tese de Mestrado, Faculdade de Ciências da Universidade de Lisboa. Portugal. 144p.

Martin, J. I. (2008). Fisheries in Madeira. Directorate-General Internal Policies of the Union. Policy Department B: Structural and Cohesion Policies. IP/B/PECH/NT/2008, PE 408.947. 25p.

Martins, M. R., Leite, A. M., Nunes, M. L. (1987). Peixe espada-preto. Algumas notas acerca da pescaria do peixe espada-preto. Instituto Nacional de Investigação das Pescas (Publicações avulsas), Lisboa, Portugal. 14p.

Mata, J., Fonseca, P., Prada, S., Rodrigues, D., Martins, S., Ramalho, R., Madeira, J., Cachão, M., Silva, C. M., Matias, M. J. (2013). O arquipélago da Madeira. In R. Dias, A. Araújo, P. Terrinha & J.C. Kullberg (*eds*) – Geologia de Portugal, Vol. II, Geologia Meso-Cenozóica de Portugal: 691-746. Escolar Editora, Lisboa.

Maunder, M. N. and Punt, A. E. (2004). Standardizing catch and effort data: a review of recent approaches. *Fisheries Research*, 70: 141-159.

Maunder, M. N., Sibert, J. R., Fonteneau, A., Hampton, J., Kleiber, P., Harley, S. J. (2006). Interpreting catch per unit effort data to assess the status of individual stocks and communities. *ICES Journal of Marine Science*, 63: 1373-1385.

Merrett, N. R. and Haedrich, R. L. (1997). Deep-Sea Demersal Fish and Fisheries. London: Chapman-Hall. 286p.

Montgomery, D. C. (2013). Design and Analysis of Experiments. Eighth Edition. John Wiley & Sons, Inc. 741 p.

Moutopoulos, D. K., and Stergiou, K. I. (2002). Length-weight and length-length relationships of fish species from the Aegean Sea (Greece). *Journal of Applied Ichthyology*, 18: 200-203.

Morales-Nin, B. and Sena-Carvalho, D. (1996). Age and growth of the Black Scabbardfish (*Aphanopus carbo*) off Madeira. *Fisheries Research*, 25: 239-251.

Morales-Nin, B, Canha, A., Casas, M., Figuereido, I., Gordo, L. S., Gordon, J., Gouveia, E., Pineiro, C. G., Reis, S., Reis A., Swan, S. C. (2002). Intercalibration of age readings of deepwater black scabbardfish, *Aphanopus carbo* (Lowe, 1839). *ICES Journal of Marine Science*, 59(2): 352-364.

Morato, T., Afonso, P., Lourinho, P., Barreiros, J. P., Santos, R. S., Nash, R. D. M. (2001). Length-weight relationships for 21 coastal fish species of the Azores, north-eastern Atlantic. *Fisheries Research*, 50: 297-302.

Morato, T., Watson, R., Pitcher, T. J., Pauly, D. (2006). Fishing down the deep. *Fish and Fisheries*, 7: 24-34.

Muñoz, D. P. and Román, E. (2000). Spanish experimental fishing: a cooperative research initiative between scientists and the local fishing industry. *ICES CM 2000*/ W:03: 18 pp.

Muñoz, P. D., Mandado, M., Gago, A., Gómez, C., Fernández, G. (2005). Brief results of a trawl experimental survey at NW Atlantic. *NAFO SCR* Doc. 05/32, Serial No. N5095.

Nakamura, I. (1984). Scombrolabracoidai, Scombroidei. In: Masuda H., Amaoka K., Araga C., Uyeno T. (Eds.) The fishes of the Japanese Archipelago. Tokai University Press, Tokyo, 224-228.

Nakamura, I. and Parin, N. V. (1993). FAO Species Catalogue. Vol. 15. Snake mackerels and cutlassfishes of the world (Families Gempylidae and Trichiuridae). An annotated and illustrated catalogue of the snake mackerels, snoeks, escolars, gemfishes, sackfishes, domine, oilfish, cutlassfishes, scabbardfishes, hairtails, and frostfishes known to date. *FAO Fisheries Synopsis*, Rome. 125(15): 136pp.

Nash, R. D. M., Valencia, A. H., Geffen, A. J. (2006). The Origin of Fulton’s Condition Factor - Setting the Record Straight. *Fisheries history*, 31(5): 236-238.

Neves, A., Vieira, A. R., Farias, I., Figueiredo, I., Sequeira, V., Gordo, L. S. (2009). Reproductive strategies in black scabbardfish (*Aphanopus carbo* Lowe, 1839) from the NE Atlantic. *Scientia Marina*, 73(2): 19-31.

Norse, E. A., Brooke, S., Cheung, W. W. L., Clark, M. R., Ekeland, I., Froese, R., Gjerde, K. M., Haedrich, R. L., Heppell, S. S., Morato., T., Morgan, L. E., Pauly, D., Sumaila, R., Watson, R. (2012). Sustainability of deep-sea fisheries. *Marine Policy*, 36: 307-320.

Ortiz, M. and Arocha, F. (2004). Alternative error distribution models for standardization of catch rates of non-target species from a pelagic longline fishery: billfish species in the Venezuelan tuna longline fishery. *Fisheries Research*, 70: 275-297.

Palazón-Fernández, J. L., Arias, A. M., Sarasquete, C. (2001). Aspects of the reproductive biology of the toadfish, *Halobatrachus didactylus* (Schneider, 1801) (Pisces: Batrachoididae). *Scientia Marina*, 65(2): 131-138.

Parin N. V., Becker, V. E. (1972). Materials on taxonomy and distribution of some trichiuroid fishes (Pisces, Trichiuroidae: Scombrolabracidae, Gempylidae, Trichiuridae). *Trudy Instituta Okeanologii*, 93: 110-204.

Parin, N. V. (1995). Three new species and new records of cutlass fishes of the genus *Aphanopus* (Trichiuridae). *Journal of Ichthyology* 35(2): 128-138.

Pajuelo, J. G., González, J. A., Santana, J. I., Lorenzo, J. M., García-Mederos, A., Tuset, V. (2008). Biological parameters of the bathyal fish black scabbardfish (*Aphanopus carbo* Lowe, 1839) off the Canary Islands, Central-east Atlantic. *Fisheries Research*, 92(2-3): 140-147.

Pauly, D. (1993). Fish byte Section Editorial. Naga, *ICLARM Quart.*, 16: 26.

Pauly, D. (1995). Anecdotes and the shifting baseline syndrome of fisheries. *Trends in Ecology and Evolution*, 10(10): 430.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., Torres Jr., F. (1998). Fishing Down Marine Food Webs. *Science,* 279(6): 860-863.

Peden A. (1974). Rare fishes including fish records of thirteen species from British Columbia. *Syesis*, 7: 47–62.

Perera, C. B. (2008). Distribution and biology of black scabbardfish (*Aphanopus carbo* Lowe, 1839) in the NW of Africa. Master Thesis in Biology and Management of Marine Resources. Science Faculty, University of Lisbon, Portugal, 71p.

Petrakis, G. and Stergiou, K. I. (1995). Weight-length relationships for 33 fish species in Greek waters. *Fisheries Research,* 21: 465-469.

Pires, R., Neves, H. C., Karamanlidis, A. (2008). The Critically Endangered Mediterranean monk seal *Monachus monachus* in the archipelago of Madeira: priorities for conservation. Fauna & Flora International, *Oryx*, 42(2): 278-285.

Pires, R. (2011). Lobos-Marinhos do Arquipélago da Madeira. Serviço do Parque Natural da Madeira. Eco do Funchal, Madeira, Portugal. 60p.

Pissara, J. Cavaco, M. H., Monteiro, A. M. (1983). Caracterização oceanográfica na região da Madeira: Determinação das massas de água no “Núcleo de Água Mediterrânica”. *Boletim do Instituto de Investigação das Pescas Portuguesas,* 10: 65-80.

Pitman, W. and Talwani, M. (1972). Sea floor spreading in the North Atlantic, *Geological Society of America Bulletin,* 83(3): 619-646.

R Core Team (2015). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.

Reis, S., Sena-Carvalho, D., Delgado, J. H., Afonso-Dias, M. (2001). Historical Overview of the black scabbardfish (*Aphanopus carbo* Lowe, 1839) fishery in Madeira Island. *Deep-Sea Fisheries Symposium,* NAFO SCR Doc. 01/103, 6p.

Rice, A. L., Billet, D. S. M., Thurston, M. H., Lampitt, R. S. (1991). The Institute of Oceanographic Sciences biology programme in the Porcupine Seabight: background and general introduction*. Journal of the Marine Biological Association UK*, 71: 281-310.

Richter, H., Lückstädt, C., Focken, U. L., Becker, K. (2000). An improved procedure to assess fish condition on the basis of length-weight relationships. *Archive of Fishery and Marine Research,* 48(3): 226-235.

Ricker, W. E. (1975). Computations and interpretation of biological statistics of fish populations. *Fisheries Research Board of Canada Bulletin.* 191: 382p.

Roa, R., Ernst, B., Tapia, F. (1999). Estimation of size at sexual maturity: an evaluation of analytical and resampling procedures. *Fishery Bulletin*, 97(3): 570-579.

Roberts. C. (2007). *The unnatural history of the sea.* Island Press, Washington D.C., USA. 457p.

Rochon, J., Gondan, M., Kieser, M. (2012). To test or not to test: Preliminary assessment of normality when comparing two independent samples. *BMC Medical Research Methodology,* 12(81): 1-11.

Rose, G. A. and Leggett, W. C. (1991). Effects of biomass-range interactions on catchability of migratory demersal fish by mobile fisheries: an example of Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Sciences,* 48: 843-848.

Santos, M. N., Gaspar, M. B., Vasconcelos, P., Monteiro, C. C. (2002). Weight-length relationships for 50 selected fish species of the Algarve coast (Southern Portugal). *Fisheries Research*, 59: 289-295.

Santos, A. R. (2013). The life history and ecology of black scabbardfish (*Aphanopus carbo* Lowe 1839) in the North-East Atlantic. PhD Thesis, University College Cork. 208p.

Santos, A. R., Minto, C., Connolly, P., Rogan, E. (2013a). Oocyte dynamics and reproductive strategy of *Aphanopus carbo* in the NE Atlantic – Implications for fisheries management. *Fisheries Research*, 143: 161-173.

Santos, A. R., Trueman, C., Connolly, P., Rogan, E. (2013b). Trophic ecology of black scabbardfish, *Aphanopus carbo* in the NE Atlantic - Assessment through stomach content and stable isotope analyses. *Deep-Sea Research I*, 177: 1-10.

Schwarz, G. E. (1978). Estimating the dimension of a model. *Annals of Statistics,* 6 (2): 461-464.

Schwarz, S., Klügel, A., Bogard, P. v. d., Geldmacher, J. (2005). Internal structure and evolution of a volcanic rift system in the eastern North Atlantic: the Desertas rift zone, Madeira archipelago. *Journal of Volcanology and Geothermal Research*, 141: 123-155.

Scientific, Technical and Economic Committee for Fisheries (STECF) (2014). Review of an assessment of the stock of black scabbardfish (*Aphanopus spp.*) around Madeira (STECF-14-15). Publications Office of the European Union. European Commission, Joint Research Centre, Luxembourg. 27p.

Shon, S., Delgado, J. M., Morato, T., Pham, C. K., Zylich, K., Zeller, D., Pauly, D. (2015). Reconstruction of marine fisheries catches for Madeira Island, Portugal from 1950-2010. Fisheries Centre, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada. Working Paper Series, nº52. 13p.

Silveira, A. B., Madeira, J., Ramalho, R., Fonseca, P., Prada, S. (2010). Notícia Explicativa da Carta Geológica da ilha da Madeira na escala 1:50.000, Folhas A e B. Secretaria Regional do Ambiente e Recursos Naturais, Região Autónoma da Madeira e Universidade da Madeira. 47p.

SRA (2014). Estratégia Marinha para a subdivisão da Madeira. Diretiva Quadro Estratégia Marinha. Secretaria Regional do Ambiente e dos Recursos Naturais. 463p.

Templeman. W. and Squires. H. J. (1963). Three records of the black scabbardfish, *Aphanopus carbo* Lowe, from the Canadian region of Western Atlantic. *Journal of the Fisheries Research Board of Canada.*, 20: 273-278.

Tesch, F. W. (1968). Age and growth. In: Methods for assessment of fish production in fresh waters. W. E. Ricker (Ed.). Blackwell Scientific Publications, Oxford, 93-123p.

Uiblein, F., Bordes, F., Castillo, R. (1996). Diversity, abundance and depth distribution of demersal deep-water fishes off Lanzarote and Fuerteventura, Canary Islands. *J. Fish Biol*. 49, 75-90.

Venables, W. N. and Dichmont, C. M. (2004). GLMs, GAMs and GLMMs: an overview of theory for applications in fisheries research. *Fisheries Research,* 70: 319-337.

Vandekerckhove, J., Matzke, D., Wagenmakers, E. (2014). Model Comparison and the Principle of Parsimony. In J. Busemeyer, J. Townsend, Z. J. Wang, & A. Eidels (Eds.), Oxford handbook of computational and mathematical psychology. Manuscript accepted pending minor revision. Oxford, UK: Oxford University Press. 181p.

Vieira, A. R., Farias, I., Figueiredo, I., Neves, A., Morales-Nin, B., Sequeira, V., Martins, M. R. Gordo, L. S. (2009). Age and growth of black scabbardfish (*Aphanopus carbo* Lowe 1839) in the sourthern NE Atlantic. *Scientia Marina,* 73S2: 33-46.

Was, A., Gosling, E., McCrann, K., Mork, J. (2008). Evidence for population structuring of blue whiting (*Micromesistius poutassou*) in the Northeast Atlantic. *ICES Journal of Marine Science*, 65: 216-225.

West, G. (1990). Methods of assessing ovarian development in fishes. *Australian Journal of Marine and Freshwater Research*, 41: 199-222.

Zbyszewski, G., Veiga Ferreira, O., Aires-Barros, L., Matias, M. J., Bravo, T. Coello, J. (1973). Notícia Explicativa da Folha das ilhas Selvagens. Serviços Geológicos de Portugal, Lisboa.

Zilanov, V. K. and Shepel, L. I. (1975). Notes on the ecology of the black scabbardfish, *Aphanopus carbo*, of the North Atlantic. *Journal of Ichthyology*, 15: 661-663.

Zuur, A. F., Leno, E. N., Elphick, C. S. (2009). A protocol for data exploration to avoid common statistical problems. *Methods in Ecology & Evolution*, 1(1): 3-14.

Zuur, A. F. and Leno, E., N. (2016). A protocol for conducting and presenting results of regression-type analyses. *Methods in Ecology and Evolution*, 7: 636-645.

APPENDIX A

1. Diagnostic plots for GSI, HSI and K$_{rel}$ data

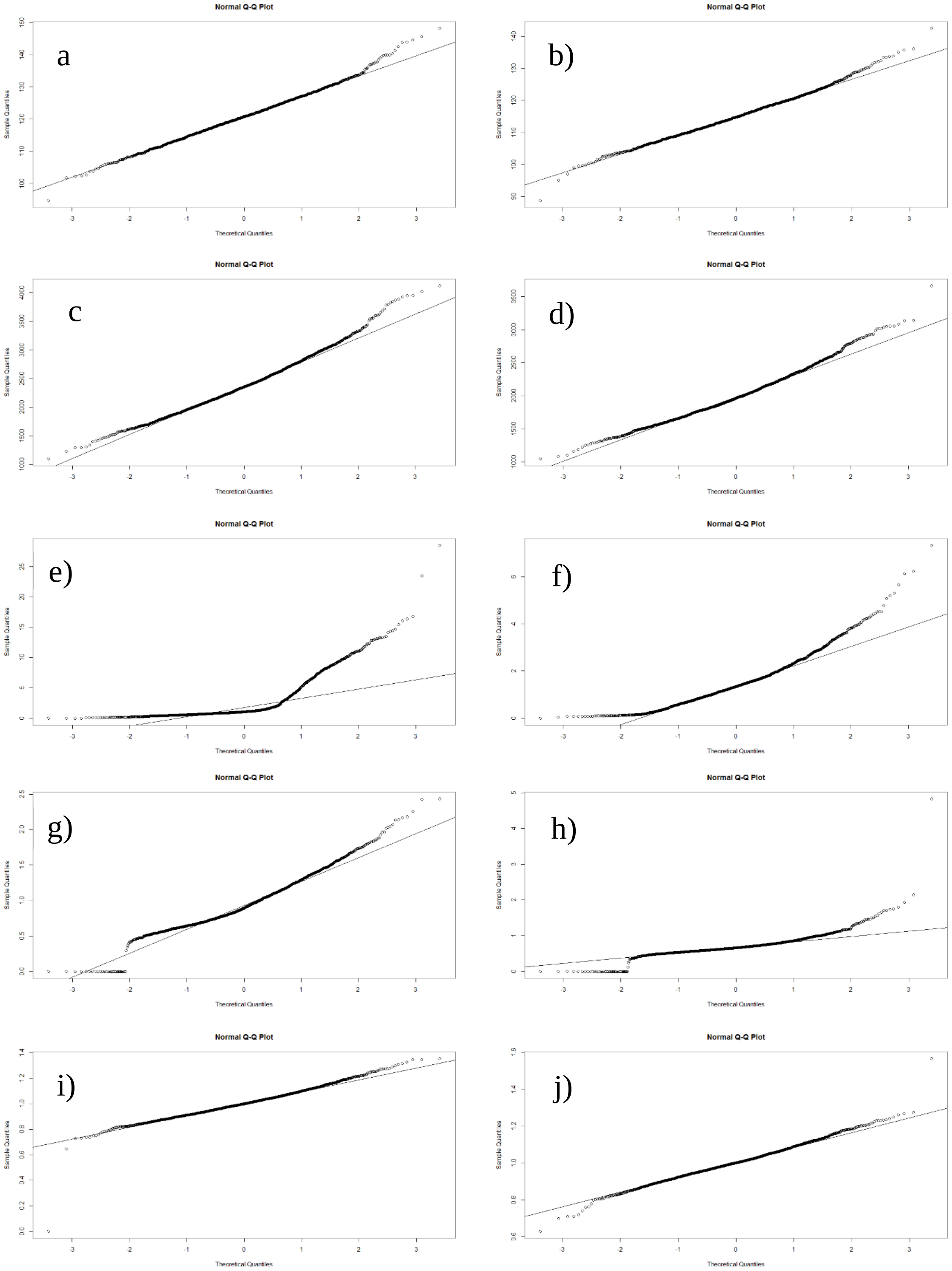


Figure 1. QQ-plots for normality assumptions considering the distributions of: a) length of females; b) length of males; c) weight of females; d) weight of males; e) GSI of females; f) GSI of males; g) HSI of females; h) HSI of males; i) K$_{rel}$ of females; j) K$_{rel}$ of males. Normality is assumed for all distributions, although graphs e), f), h) and i) are rather skewed.

APPENDIX B

1. Pearson correlation frame between predictors

```
                            data_raw.Days_sea data_raw.Fishing.days
data_raw.Days_sea                        1.00                  0.93
data_raw.Fishing.days                    0.93                  1.00
data_raw.Fishing.trips                   0.01                 -0.03
data_raw.Fishing.operations              0.78                  0.77
data_raw.Classe_LOA                      0.53                  0.49
data_raw.Classe_Vessel.KW                0.43                  0.35
data_raw.Soaking.time                    0.68                  0.72
data_raw.Classe_GT                       0.53                  0.51
data_raw.Ano                            -0.05                 -0.23
data_raw.Mês                            -0.05                 -0.07
                    data_raw.Fishing.trips data_raw.Fishing.operations
data_raw.Days_sea                     0.01                        0.78
data_raw.Fishing.days                -0.03                        0.77
data_raw.Fishing.trips                1.00                       -0.01
data_raw.Fishing.operations          -0.01                        1.00
data_raw.Classe_LOA                   0.01                        0.40
data_raw.Classe_Vessel.KW             0.01                        0.29
data_raw.Soaking.time                -0.02                        0.72
data_raw.Classe_GT                   -0.01                        0.37
data_raw.Ano                          0.07                        0.11
data_raw.Mês                          0.05                       -0.06
                         data_raw.Classe_LOA data_raw.Classe_Vessel.KW
data_raw.Days_sea                       0.53                      0.43
data_raw.Fishing.days                   0.49                      0.35
data_raw.Fishing.trips                  0.01                      0.01
data_raw.Fishing.operations             0.40                      0.29
data_raw.Classe_LOA                     1.00                      0.53
data_raw.Classe_Vessel.KW               0.53                      1.00
data_raw.Soaking.time                   0.33                      0.22
data_raw.Classe_GT                      0.85                      0.57
data_raw.Ano                           -0.07                     -0.04
data_raw.Mês                           -0.01                     -0.02
                 data_raw.Soaking.time data_raw.Classe_GT data_raw.Ano
data_raw.Days_sea                   0.68               0.53        -0.05
data_raw.Fishing.days               0.72               0.51        -0.23
data_raw.Fishing.trips             -0.02              -0.01         0.07
data_raw.Fishing.operations         0.72               0.37         0.11
data_raw.Classe_LOA                 0.33               0.85        -0.07
data_raw.Classe_Vessel.KW           0.22               0.57        -0.04
data_raw.Soaking.time               1.00               0.36        -0.09
data_raw.Classe_GT                  0.36               1.00        -0.15
data_raw.Ano                       -0.09              -0.15         1.00
data_raw.Mês                       -0.06              -0.02         0.02
                            data_raw.Mês
data_raw.Days_sea                  -0.05
data_raw.Fishing.days              -0.07
data_raw.Fishing.trips              0.05
data_raw.Fishing.operations        -0.06
data_raw.Classe_LOA                -0.01
data_raw.Classe_Vessel.KW          -0.02
data_raw.Soaking.time              -0.06
data_raw.Classe_GT                 -0.02
data_raw.Ano                        0.02
data_raw.Mês                        1.00
```

2. Diagnostic plots for the linear model

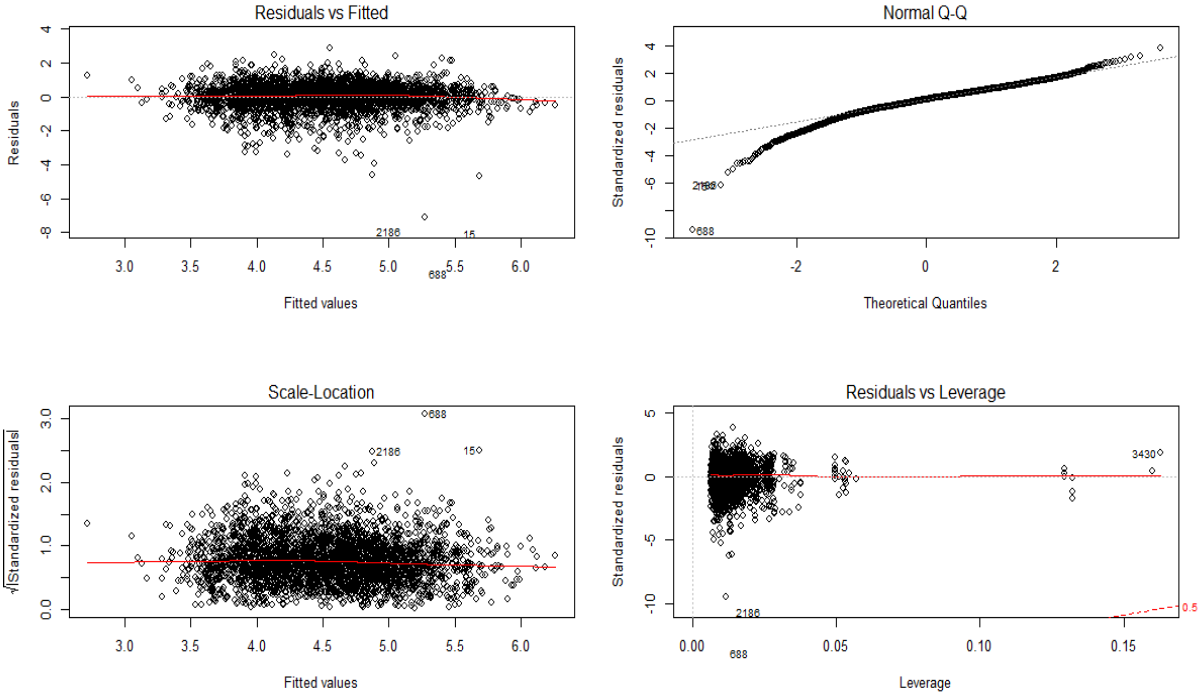


Figure 2. Residual plots of the standardized model of LPUE data of *Aphanopus spp.* in the period 2008-2015. The top left graph represents deviance residuals vs. fitted values, the top right graph represents the normal QQ-plot, the bottom left graph represents the square root of the deviance residuals vs. fitted values, and the bottom right represents the standardized deviance residuals vs. leverage and also the Cook's distance. The overall analysis allows to state that no great violations were found.

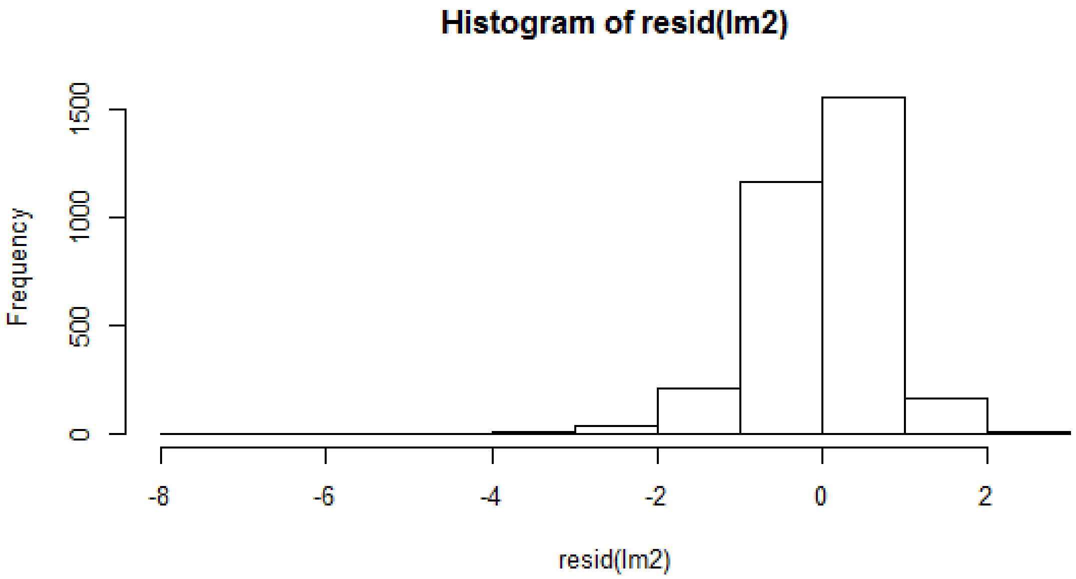


Figure 3. Histogram plot of the log-normal distribution of residuals. The distribution is around the origin, confirming the normality assumption.

3. Fishing effort in Madeira EEZ and subjacent areas

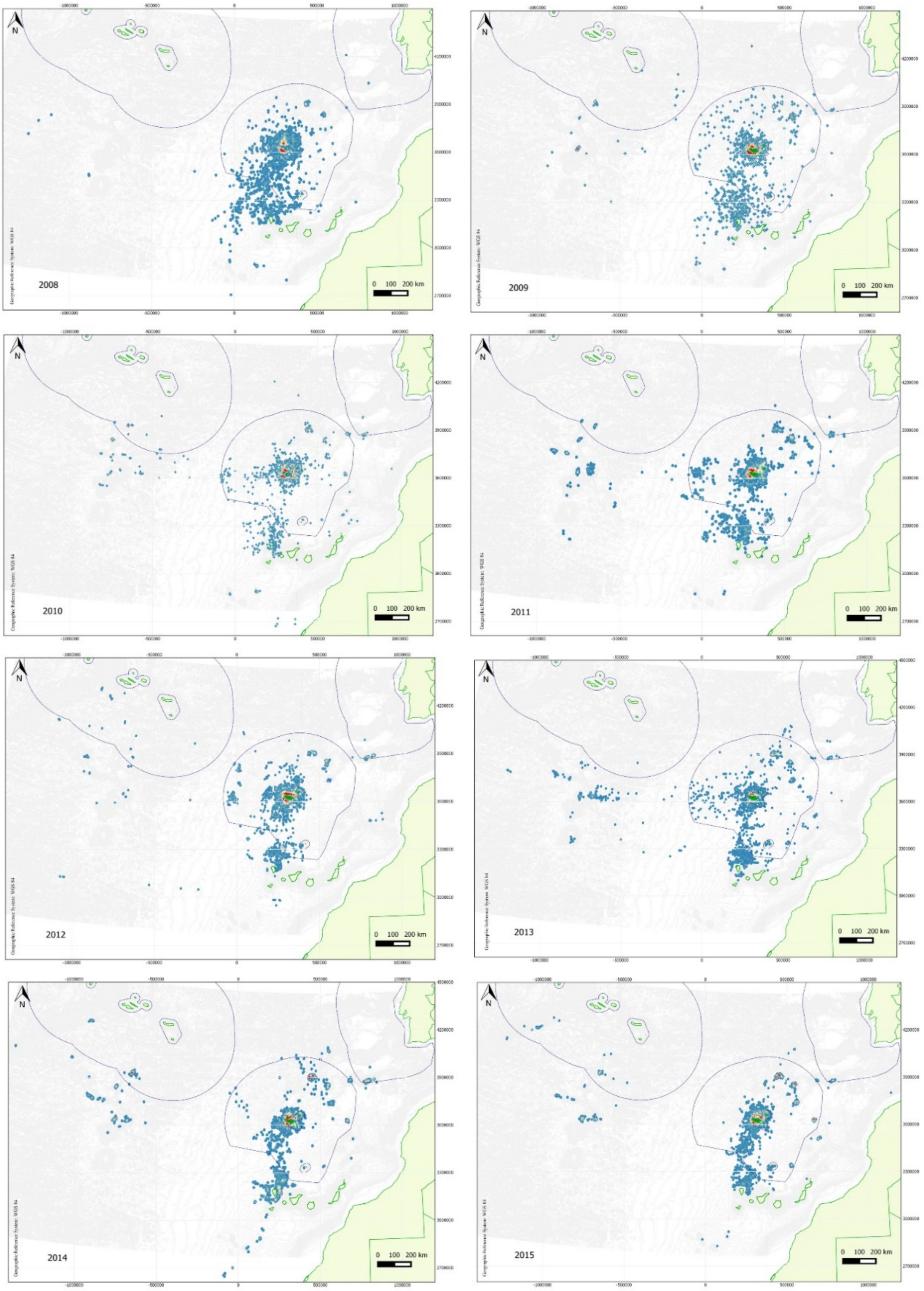


Figure 4. Annual comparison of the spatial distribution of fishing effort, obtained from logbook registers (2008-2015). It is clearly visible the concentration of fishing vessels around Madeira and Porto Santo Islands, and also in fishing banks on the north part of the EEZ. Also, the recent pattern is seen as vessels venture northwest, to the Azores, and south to the Canary Islands and further, to improve catch rates (from Delgado *et al.*, 2016).

4. CPUE vs. Abundance plot

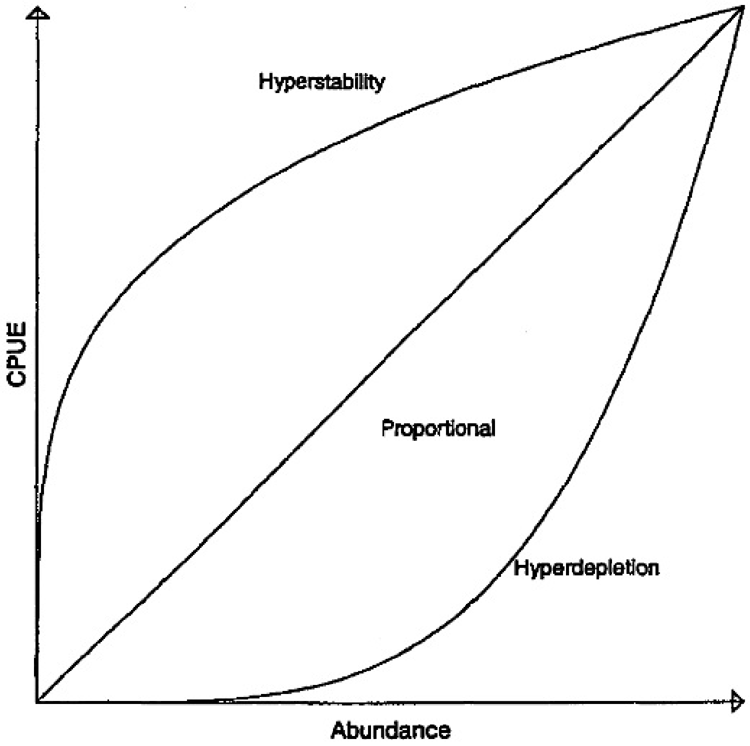


Figure 5. Three possible relationships between CPUE and abundance: Proportionality; Hyperstability; and Hyperdepletion. Under standard model assumptions, CPUE is assumed to be proportional to abundance. Hyperstability occurs when catchability increases with decreasing stock size. Hyperdepletion, where catchability drops faster than the population and therefore results in an under-estimate of abundance (from Hilborn & Walters, 1992).