UNIVERSIDADE DOS AÇORES
DEPARTAMENTO DE OCEANOGRAFIA E PESCAS

ANTHROPOGENIC IMPACTS IN THE DEEP SEA OF THE AZORES: FISHING AND LITTER

By

Christopher Kim Pham

DISSERTAÇÃO APRESENTADA À UNIVERSIDADE DOS AÇORES PARA OBTENÇÃO DO GRAU DE DOUTOR NO RAMO DE CIÊNCIAS DO MAR, ESPECIALIDADE EM ECOLOGIA MARINHA

Horta, 2014

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Christopher Kim Pham

Under the supervision of:

Dr. Telmo Morato
Centro do IMAR da Universidade dos Açores

Dr. Eduardo Isidro
Departamento de Oceanografia e Pescas
Universidade dos Açores

and co-supervision of:

Dr. Ricardo Serrão Santos
Departamento de Oceanografia e Pescas
Universidade dos Açores

UNIVERSIDADE DOS AÇORES
Horta, 2014

“What could be stranger than the unknown danger that lies on the ocean floor?” - Neil Young

This research was funded by the the Fundação para a Ciência e a Tecnologia (FCT, Grant number (SFRH/ BD/31286/2009) and conducted in the framework of the EU FP7 projects CoralFISH (FP7 ENV/2007/1/21314 4) and HERMIONE (FP7 ENV/ 2008/1/226354)

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

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Acknowledgements

I am grateful to many people that have supported and inspired me over these past four years. I would like to sincerely thank my supervisor Telmo Morato, for his guidance, patience, motivation, availiability and dedication to the work presented in this thesis. He has always been available when ever I needed him and his mentorship was paramount in shaping this work. I am also very grateful to Eduardo Isidro for his continuous support and encouragement since my arrival in Faial, 8 years ago. He has always been readily available when I needed anything. I would like to sincerely thank Ricardo Santos for his constant support in my participation to meetings, workshops and conferences. I would like to extend my thanks to Filipe Porteiro for his enthusiasm about the subject, support and for the many insightful discussions on some of the ideas developed in this thesis. Thanks are also due to Gui Menezes for his collaboration and sharing the data from the demersal fisheries surveys along with the numerous discussions on the subject.

Thanks to the coralFISH and HERMIONE participants, especially to Eva-Ramirez Llodra who let me lead the work on litter distribution in European waters and for guiding me throughout the entire process of dealing with a lot of different authors. To Antun Purser and Melanie Bergmann who encouraged me in taking the task of analysing the litter data and for their assistance, along with the rest of the co-authors, in writing the paper. Thanks to Dr. Dirk Zeller and Dr. Sarah Harper from the Fisheries Centre, University of British Columbia for their guidance and support in the first chapter of this thesis. I would like to thank a number of people that contributed to this work through numerous discussions, data sharing and friendship. These include Pedro Afonso, Alan Bolten, Andreia Braga-Henriques, Cristina Brito, Angela Canha, Gilberto Carreira, Maria João Cruz, Hugo Diogo, Rogério Ferraz, Les Gallagher, João Gonçalves, Monica Inacío, Eduardo Isidro, Miguel Machete, Gustavo Martins, Helen Martins, Valentina Matos, Mário Rui Pinho, João Gil Pereira, José-Nuno Pereira, Rui Prieto, Adriana Ressurreição, Dália Reis, João Santos, Marco Santos, Iris Sampaio, Hélder Silva, Fernando Tempera, and Frederic Vandeperre.

I would also like to thank all the staff from DOP/IMAR for their daily help and assistance, especially Ricardo Medeiros, Sandra Andrade and Sandra Silva. Thanks are also due

to Paulo Martins and Victor Rosa of Águas Vivas and to Renato Martins during our good times "roving" over Condor Seamount. I would also like to thank all the fishery observers who have been collecting some of the data used in this thesis, especially Tiago Bento and Vitor Monteiro.

To my friends back home and elsewhere that unfortunately, I do not get to see much but that are always there when I need them: Vince, Tomi, Tichkebal, Flipi, Max, Mony, Yves, Renée, Blondinos...and so many others. To all my band members; Fausto, Pieta, Lau, Gira, Batata, Mota, Mauro, Mark, Velmano and Roger who got the patience of rescheduling many rehearsals and gigs, in order to let me work on this thesis but above all for all those good times spent together.

To my beloved Maria & the animals for bearing with me during all those "computer nights" and the unconditional love...To Geca who has provided her nice and comfortable home in Sintra, where I could work on this thesis during my rough health times in the mainland.

And of course I would like to especially thank my wonderful parents; Gropo and Mamamex and my lovely sister "Tête de hibou" for being my main driving force. And finally, I dedictate this thesis to my grand parents"Pipo&Minette".

Abstract

The deep sea is the largest biome on earth, covering approximately 60% of the Earth's solid surface and representing 90% of the oceans by volume. Due to its limited accessibility, it is the least understood, yet one of the richest ecosystems on the planet. It provides a wealth of resources and is crucial to our lives through the services it provides. Although the oceans have been utilized by humans for millennia, it is only recently, through technological developments, that humans have begun exploiting the deep ocean. Current and future activities directly affecting the deep sea include fishing, waste disposal, oil, gas and mineral extraction and bio-prospecting. There is mounting evidence suggesting that the deep sea is highly vulnerable to anthropogenic disturbance and that the conservation of deep sea habitats should be a priority. Yet, we lack comprehensive assessments on the effects of most human activities impacting the deep sea. The objectives of this work are to further characterize and understand two important threats for deep sea ecosystem off the Azores; fishing and litter disposal.

To better assess the level of pressure exerted by fishing on deep sea living resources, the first step of this thesis consisted in reconstructing total fisheries removals within the Azores territory, including Illegal, Unreported and Unregulated catches. Reconstruction of total fisheries catch demonstrated that demersal fishing in the Azores has significantly increased over the past 30 years and that it is currently a key component of the fishing sector. The results revealed the existence of substantial removals of many deep sea fishes that are unaccounted in official catch statistics. We showed that unreported catches of some deep-water sharks (~10 species), silver scabbard fish (*Lepidopus caudatus*) or alfonsinos (*Beryx* spp.) can greatly surpass the amounts officially reported. The information obtained in this chapter fill an important gap on our knowledge of the impact of fishing in the deep sea, with implications for the management of deep-sea fisheries in the region.

The destruction of deep-sea habitats by bottom fishing is another important environmental concern of deep-sea fishery tackled in this study. The results obtained on the impact of demersal fishing in the Azores, integrating bycatch data from commercial activities together with in situ data, showed a reduced, yet not negligible impact on benthic habitats by longline fishing. Whilst there was no bycatch of epibenthic organisms from handline, deep-water longline will mostly impact epibenthic organisms with a complex morphology, having therefore an unbalanced impact in the ecosystem. Accordingly, management measures should be implemented to prevent eventual long-term shifts in community structure. Yet in

comparison with bottom trawling, the impacts are minimal and thus, it is suggested that longline can be an alternative to trawling in other parts of the world.

Cold-Water Corals (CWC) increase habitat complexity, believing to act as feeding, reproductive, nursery and refuge areas for a high number of invertebrates and fish species. Therefore, in chapter II, I analysed the ecological impacts of CWC removals from fishing on deep-sea fish species (*Helicolenus dactylopterus dactylopterus*, *Pagellus bogaraveo*, *Mora moro*, *Conger conger*, *Phycis phycis*, *Pontinus kuhlii*). Using data collected during experimental longline surveys over several years, we modeled the catch of demersal fish in relation to the presence of Vulnerable Marine Ecosystems (VMEs) based on the standardized bycatch levels obtained in the second chapter. Total fish catch was higher inside VMEs but the relationship between fish and VMEs varied among fish species. Species specific models showed that the presence of VMEs was only important for two rockfish species: *P. kuhlii* (juveniles and adults) and *H. d. dactylopterus* (juveniles). Although demonstrating a functional relationship between fish and VMEs is challenging, we suggest that VMEs act as an important habitat for those two species.

The present work also highlighted an additional impact of fishing on benthic habitats that needs to be considered when understanding the full ecological footprint of human activities in the deep sea. The analysis of underwater images on Condor seamount and in other location across Europe showed lost fishing gear to be widespread on the seafloor. Litter density on the summit of Condor seamount, where most fishing activity takes place was 1439 litter items km^{-2}, whereas on the deeper northern flank, estimates indicate lower litter densities. Most of the lost fishing lines were observed entirely or partly entangled in the locally abundant gorgonians *Dentomuricea. aff. meteor* and *Viminella flagellum*. The analysis of data collected during 540 video and trawl surveys across 31 other sites in European waters, revealed litter to be present in much deeper and more remote places, such as the Charlie-Gibbs Fracture Zone across the Mid-Atlantic Ridge. The results showed that generally, the highest litter density occurs in submarine canyons, whilst the lowest density can be found on continental shelves and on ocean ridges. In comparison with other locations, litter densities on Condor seamount was intermediate, being lower than some submarine canyons located close to large agglomerations such as the Lisbon Canyon, the Blanes Canyon, the Guilvinec Canyon or the Setúbal Canyon. The presence of litter on these settings is of particular concern because they harbour VMEs (such as CWC) that have reduced capacity to recover from disturbance events and for which conservation is a global priority.

My thesis work suggests that sustainable management of deep-sea resources must include all likely effects of human activities. Ecosystem-based management of the deep-sea in the Azores needs to address fisheries discards, damages to benthic habitats, and litter disposal.

Resumo

O mar profundo é o maior bioma da Terra, cobrindo aproximadamente 60% da sua superfície sólida, e representando cerca de 90% do volume dos oceanos. Ainda que este seja um dos ecossistemas mais ricos do planeta, é, devido à sua enorme dimensão e difícil acessibilidade, o menos estudado e compreendido. Ele oferece-nos uma riqueza imensa de recursos e é crucial para as nossas vidas através dos serviços que nos presta. Embora os oceanos sejam utilizados pelo Homem desde há milénios, só recentemente, na sequência de desenvolvimentos tecnológicos consecutivos, se começou a explorar o oceano profundo. As atividades atuais e futuras que afetam e afetarão diretamente o oceano profundo são essencialmente: a pesca, o lixo, a extração de óleo, de gás e de minério, e ainda a bioprospecção. Havendo uma evidência crescente de que o fundo do mar é altamente vulnerável a perturbações antropogénicas e que a conservação dos habitats de profundidade deve ser uma prioridade, não há, ainda, avaliações abrangentes sobre o efeito e impacto da maioria das atividades humanas no mar profundo. Os objetivos deste trabalho são, essencialmente, os de caracterizar e entender duas ameaças importantes para o mar profundo dos Açores: a pesca e o lixo.

Para melhor avaliar o nível de pressão exercida pela pesca sobre os recursos vivos do mar profundo, a primeira etapa deste trabalho consistiu na reconstrução das capturas totais efetuadas pela pesca em águas açorianas, incluindo as capturas ilegais, as não declaradas e as não reguladas. Esta reconstrução demonstrou que a pesca de espécies demersais aumentou significativamente ao longo dos últimos 30 anos e que é, atualmente, um componente-chave no sector das pescas açorianas. Os resultados revelaram que as estatísticas oficiais de capturas, para diversas espécies de águas profundas, são incompletas ou até omissas, uma vez que as capturas não declaradas de alguns tubarões de profundidade (~ 10 espécies), de peixe-espada branco (*Lepidopus caudatus*) ou de imperadores, quando a cota é atingida, pode superar em muito os valores notificados oficialmente.

Um outro aspeto importante abordado neste trabalho, é o da destruição de habitats pela pesca de fundo. Os resultados obtidos sobre o impacto da pesca demersal dos Açores, integrando dados de captura acessória com dados in situ, evidenciam que o palangre de fundo tem um impacto relativamente reduzido, mas não negligenciável, sobre os habitats bentónicos. De facto, enquanto a linha de mão é uma arte que não apresenta captura acidental, o palangre

de fundo interage com os organismos epibentónicos de morfologia externa complexa, tendo, assim, algum impacto no ecossistema. Contudo, os impactos da pesca com palangre de fundo, quando comparada com a pesca exercida com arrasto de fundo, é mínimo, pelo que o palangre tem surgido, noutras partes do mundo, como uma alternativa ao arrasto.

Os corais de água fria aumentam a complexidade do habitat, funcionando como áreas de alimentação, reprodução, refúgio e crescimento para um elevado número de espécies de invertebrados e de peixes. Assim, no capítulo II foram analisados os impactos ecológicos da remoção de corais de água fria pela pesca, sobre algumas espécies de peixes de profundidade (*Helicolenus dactylopterus dactylopterus*, *Pagellus bogaraveo*, *Mora moro*, *Conger conger*, *Phycis phycis*, *Pontinus kuhlii*). Para tal, e usando-se os dados recolhidos ao longo de vários anos, , nas campanhas regulares de pesca com palangre para a monitorização de recursos vivos, modelou-se as capturas de espécies demersais tendo em consideração a presença de Ecossistemas Marinhos Vulneráveis (EMVs) e os níveis de captura acessória padronizada obtidos no segundo capítulo. Observou-se que a captura total de peixes é mais elevada no interior das EMVs, sendo as relação variável e específica. Os modelos específicos mostraram que a presença de EMVs é importante essencialmente para duas espécies: *P. kuhlii* (juvenis e adultos) e *H. d. dactylopterus* (juvenis). Assim, e embora a demonstração da existência de uma relação funcional entre os peixes e EMVs seja desafiante, sugere-se que as VMEs constituem um habitat importante para estas duas espécies.

Neste trabalho, para melhor se compreender a pegada ecológica das atividades humanas no mar profundo, também se estudou o impacto adicional da pesca sobre os habitats bentónicos. A análise de imagens subaquáticas do monte submarino Condor e de outros locais da Europa, mostrou que as artes de pesca perdidas se encontram largamente espalhadas pelo fundo do mar. No monte submarino Condor, a densidade de lixo observada no cume, local em que a maioria das atividades de pesca ocorre, foi de 1.439 itens km-2, enquanto que no flanco norte, numa zona mais profunda, as estimativas indicam densidades de lixo inferiores. A maior parte das linhas de pesca perdidas foram observadas, no todo ou em parte, enredadas em gorgónias localmente abundantes: *Dentomuricea. aff. meteor* e *Viminella flagelum*. A análise dos dados recolhidos por 540 vídeos e arrastos, em 31 locais situados em águas europeias, revelou a presença de lixo em lugares profundos e remotos, tais como na Fratura Charlie-Gibbs, na Dorsal Meso-Atlântica. Os resultados mostraram que, em geral, a maior densidade de lixo ocorre em canhões submarinos, enquanto que na plataforma continental e nas dorsais oceânicas a densidade é mais baixa. Em comparação com outros locais, a densidade de lixo observada no monte submarino Condor é intermédia, sendo menor do que a observada nalguns canhões submarinos localizados perto de grandes aglomerações, como o de Lisboa, o Blanes, o Guilvinec ou o de Setúbal. A presença de lixo nestes locais é particularmente preocupante, uma vez que neles existem ecossistemas marinhos vulneráveis (EMVs, e.g. corais de água fria), que possuem uma capacidade reduzida de resistir e de recuperar de perturbações ambientais, pelo que a sua conservação é uma prioridade global.

De um modo geral, este trabalho sugere que a gestão sustentável dos recursos do oceânico profundo deve incluir todos os efeitos das atividades humanas. No caso particular dos Açores, a gestão dos recursos vivos marinhos, se baseada no funcionamento dos ecossistemas, deve ter em consideração as rejeições da pesca, os danos induzidos pela pesca aos habitats bentónicos e a acumulação de lixo.

General Introduction

The oceans are one of humanity's most important natural resources, critical to the functioning of the Earth's life-support system and directly affecting human welfare. Human exploitation of marine resources dates back to prehistoric times (O'Connor et al., 2011), growing and diversifying as technology development opened new ways of using ocean assets. Today, the oceans are exploited for food (fisheries and aquaculture), energy (oil and gas, methane hydrates and biofuels), minerals (salt, sand, gravel) and for bioactive metabolites that may be utilised as drugs. As a result, the world's economic output is much dependent on activities taking place in the ocean.

The anthropogenic activities occurring in the oceans have experienced an exponential growth over the past century, often described as the "colonisation of ocean space". After World War II marine fisheries and aquaculture have increased significantly and global fish consumption has doubled (FAO, 2014). The steady decline of inland resources shifted many land-based activities into the oceans. Oil and gas extraction from the oceans has sharply increased over the past century, contributing nowadays to approximately one-third of the world's oil and gas production (Kaiser and Snyder, 2013). Similarly, sand and gravel dredging has shifted into the marine environment as resources in traditional land quarries and riverbeds have diminished significantly (Cooper et al., 2008).

In addition to extractive activities, the oceans are important as an artery for commerce, tourism, recreational activities and, in the past, for waste disposal (munitions, radioactive, chemicals etc...). Presently, it is estimated that 67% of the global population lives on the coast or within 60 km of the coastline (Mellinger et al., 2000). It is expected that the population living on the coast will double in the next 20 years (EEA, 1999). As a result, the history of ocean usage is not about to end. New activities, such as the production of biofuels derived from marine algae will significantly increase the usage of ocean-space (Chisti, 2008). With the recent advances in undersea technology, mineral extraction in the deep sea is slowly coming to a reality (Halfar and Fujita, 2007). In addition, the oceans are now seen as one of the several carbon sequestration alternatives to counteract the accelerating rise in anthropogenic greenhouse gases (Smetacek et al., 2012). The past decade has also experienced an increase use of marine organisms as a source of structurally unique natural products that show pronounced pharmacological activities (Molinski et al., 2009).

Many studies have demonstrated that anthropogenic activities profoundly changed marine systems at a global scale, resulting in significant loss of biodiversity (Fahrig, 2003; Myers and Worm, 2003; Pandolfi et al., 2003; Pauly et al., 1998; Thrush and Dayton, 2002; Worm et al., 2006) and eventually disrupting key ecosystem goods and services (Cardinale et al., 2012). A study integrating archaeological, paleontological, historical, and ecological records demonstrated that human-induced changes in coastal water have dramatically accelerated over the past 150 to 300 years (Lotze et al., 2006). The estimates suggest that human activities occurring in shallow waters have depleted >90% of important species and have destroyed >65% of seagrass and wetland habitat (Lotze et al., 2006). While the negative impacts of human activities in coastal ecosystems are well established (Jackson et al., 2001), the impacts in the deep sea are only starting to emerge. Furthermore, the inaccessibility of the deep sea has kept it virtually unknown to most people for very long. As a result, natural or anthropogenic impacts in the deep sea have been overlooked compared to similar-magnitude processes on land or coastal habitats.

Human activities impacting the deep sea; expansion and threats

Prior to the 1970s, the deep-sea floor was regarded as an area characterised by low biodiversity and primary production, without seasonality and with sparse marine life: “a monotonous desert” (Kunzig, 2000). With this view in mind, the United Nations Convention on the Law of the Sea (UNCLOS), in 1972, promoted the exploitation of biological and mineral resources in the deep sea. While the overall production of deep-sea fishes (Gulland, 1971), minerals and oil was recognised to be large (Gulland, 1971; Kvenvolden, 1980; Mero, 1965), these resources were poorly known, believed to be too scattered, and inaccessible to justify commercial exploitation. Yet, it did not take long for the technological and scientific development, coupled with the depletion of terrestrial and coastal resources to incentive the exploitation of marine resources into deeper waters (Davies et al., 2007; Glover and Smith, 2003; Ramirez-Llodra et al., 2011).

Anthropogenic threat in the deep sea can be either direct, such as fishing, mining of deep-sea mineral resources, dumping and hydrocarbon exploitation or indirect, such as increasing atmospheric CO_2 levels leading to significant changes in the chemistry of the ocean..

Oil industry

With the gradual depletion of terrestrial oil resources, the oil industry first expanded from land operations into inland waterways and then towards offshore areas. Offshore barges for exploration started to be used in 1950 and in the 1980s oil exploration was common at 300 meters depth (Sandrea and Sandrea, 2007). Until the 1990s, offshore oil production was limited to shallow water (<400m), but important deep-water (>400meters) resources were starting to be discovered (Sandrea and Sandrea, 2010). By 2000, deep-water production rapidly reached 1.5 million barrels a day and has since almost tripled. Ultra deep-water (>1500 meters) oil production was initiated in the Gulf of Mexico in 2005 and has grown significantly worldwide. Presently, exploratory activities for oil and gas extraction are common down to more than 3000 meters and current deep-water (and ultra deep-water) oil production is estimated to be 5 to 6 million barrels a day (Sandrea and Sandrea, 2010).

Oil production is expected to keep increasing in the coming years and spread into new areas, notably deep under the ice sheet of the Arctic (Barbier et al., 2014). Unlike onshore oil production, offshore production is consistently growing over the years (Sandrea and Sandrea, 2007), suggesting both deep and ultra deep-water to be major contributors to global supply needs in the coming decades.

Offshore oil extraction poses significant threats for deep-sea ecosystems (Glover and Smith, 2003). All aspects of the offshore oil exploitation process cause environmental impacts, from the seismic surveys used for locating the oil (Keevin and Hempen, 1997), to drilling (Bakke et al., 2013) and to the platforms themselves (Glover and Smith, 2003). Although some of these impacts are punctual, operating offshore platforms create various chronic pollution events with considerable negative effects on marine life. For example, drilling muds used for the lubrication and cooling the drill pipe can inhibit larval settlement of certain marine invertebrates and significantly increase mortality of nearby fauna (Raimondi et al., 1997). In addition, the increased sedimentation by drilling muds reduce the growth rate of cold-water corals (Larsson et al., 2013) and the overall megafauna abundance (Jones et al., 2012). However, the most important environmental impacts associated with operating oil rigs have been caused by accidental discharges, as dramatically illustrated by the 2010 Gulf of Mexico Deep water Horizon (DWH) oil spill, the largest oil spill into the ocean in world history. While the impacts of the DWH oil spill on pelagic ecosystem (Incardona et al., 2014) is more obvious to the general public, the effects was also devastating for neighbouring deep-sea ecosystems (Mason et al., 2014; Montagna et al., 2013; White et al., 2012) and the fisheris it supported (Sumaila et al., 2012). Though the long-term effects of the spill remain uncertain, the most recent research suggests some severe long-lasting damages, including wide spread destruction of entire cold-water coral ecosystems (Fisher et al., 2014). The significance of the environmental impacts of such disasters depends on the frequency of their incidence, which is usually low. Future expansion of offshore activities will certainly increase the threat, especially considering that the probability of accidents increases of about 8.5% with every ~30 m of platform depth (Muehlenbachs et al., 2013).

Fisheries

Global fisheries followed a similar course of action to the oil industry. The steady invasion of the deep ocean by the world's fishing fleets has been well described (Koslow et al., 2000; Morato et al., 2006; Watson and Morato, 2013) and is widely recognised as a growing threat to deep-sea ecosystems (Norse et al., 2012). Similar to what happened with oil extraction, the decline in catches from the traditional coastal fisheries in the 1950s, has obliged fisherman to first spread further offshore and southward to eventually reach Antarctic waters (Norse et al., 2012). As demand for fish kept on increasing and significant improvements in gear and boat technology allowed longer trips at sea, deep-water fish stocks were the next obvious target. Adding to this was the introduction of tight regulations for inshore stocks, restricting fishing opportunities in many continental shelf areas (Devine et al., 2006). The increased importance of deep-water fisheries in global landings was demonstrated by Morato et al. (2006), who showed that the global mean depth of fishing has increased by 42 m since the 1950s. However, more recent estimates, taking into account both the shift of depth between and within species, showed a stronger increase in the mean depth of fishing of about 350 m (Watson and Morato, 2013).

Research on deep-sea fish stocks and their habitats has not kept pace with the rapid development of deep-water fisheries. Consequently, their management has been weak and not sufficiently science-based to prevent stock collapse and irreversible damages to deep-sea habitats (Devine et al., 2006). The combination of very low target population productivity, nonselective fishing gear, damage to benthic habitats and the fragile regulatory regimes implies that, with very few exceptions, most deep-sea fisheries are considered to be unsustainable; having collapsed or are beginning to show warning signs of population decline (Norse et al., 2012).

Waste dumping

For decades, it was common practice to dump all kind of wastes into the deep sea. For example, at the end of World War II, several million tonnes of dangerous wastes (including chemical weapons) were dumped into the waters surrounding the UK and other European countries (Thiel et al., 1998). Similarly, nuclear submarines or large numbers of drums containing low and intermediate-level radioactive wastes (Smith et al., 1988) and pharmaceutical wastes (Peele et al., 1981) have been dumped into the deep sea. Although general dumping was banned by the London Dumping Convention (LDC) of 1972 (Thiel et al. 1998), it was only in 1993 that a dumping ban of radioactive waste was agreed by the parties of the LDC (Glover and Smith, 2003). With the existing bans on ocean disposal, it seems unlikely that deep-ocean dumping of these hazards will be politically or publicly acceptable in the future. However, further research is urgently required to evaluate the impacts of this kind of disposal and implement monitoring programs to ensure the absence of radiation leakage from the sediment.

Litter disposal

At a much larger scale and volumes, more conventional wastes (mainly plastics) are being illegally dumped from boats or being transported from the coasts and river discharges and into the ocean, part of which eventually sinking to the deep sea (Derraik, 2002). With the advance in underwater imaging technology (e.g. dropped down camera, ROV, AUV or submersibles), it is only very recently that litter has been recognised to be widespread in the deep sea across the globe (Bergmann and Klages, 2012; Miyake et al., 2011; Ramirez-Llodra et al., 2013; Schlining et al., 2013; Watters et al., 2010; Wei et al., 2012). While the impacts of marine litter on marine organisms inhabiting shallow waters have received much attention, the impacts in deep-sea fauna are poorly known (Derraik, 2002). So far, there is only one report of plastic debris ingestion in deep-sea fish (Anastasopoulou et al., 2013). Entanglement in lost fishing line has been reported for benthic biota such as corals (Bo et al., 2014) while "ghost fishing" in deep-sea nets is another consequence of derelict fishing gear (Ramirez-Llodra et al., 2010; Ramirez-Llodra et al., 2013).

Microplastics is probably the most preoccupying issue related to plastic pollution in the marine environment, for which the full scale of its effects are poorly known (Law and Thompson, 2014).The recent discovery of microplastics in deep-sea sediments suggest that this emergent form of pollution is more severe than previously anticipated (Van Cauwenberghe et al., 2013b). There has been an increasing amount of reports of microplastic ingestion by many different organisms (Baulch and Perry, 2014; Cole et al., 2013; Cole et al., 2014; Davison and Asch, 2011; Frias et al., 2014; Graham and Thompson, 2009; Lusher et al., 2013; Rochman et al., 2013; Setala et al., 2014; Watts et al., 2014). Some animals have been shown to retain particles after ingestion (Browne et al., 2008), eventually disrupting physiological processes (Wright et al., 2013a). One of the most preoccupying impact of microplastics is the transfer of chemicals (e.g. polychlorinated biphenyls (PCBs)) across trophic levels with possible dramatic consequences for entire ecosystems (Andrady, 2011; Cole et al., 2013; Farrell and Nelson, 2013; Murray and Cowie, 2011). Although such effects have not been demonstrated for deep-sea organisms, there are no apparent reasons to believe it to be different, especially since the seafloor may act as a sink for microplastics in the marine environment (Cózar et al., 2014). As the world population keeps growing, the amount of litter produced will inevitably increase and larger amounts will find its way into the ocean. Marine litter will possibly become the next significant threat to deep-sea ecosystems.

Mining

The deep sea was recognised as a potential source of rare metals since the 1960s (Mero, 1965). Yet, the first exploration and feasibility studies were only conducted in the 1980s on the East Pacific Rise (Crawford et al., 1984) and in the Red Sea (Amann, 1985). The reduced demand for precious metals and the technical challenges associated with mining the deep sea has delayed its implementation to our present day. With land-based minerals becoming depleted, the demand for rare metals used in modern technologies has recently exploded, making deep-sea deposits a new source of supply to commercial operators (Halfar and Fujita, 2007). Large sources of copper, zinc, silver and gold ores have been identified in seafloor massive sulphide (SMS) deposits at deep-sea hydrothermal vents in many areas around the world (Van Dover, 2011). There is a particular interest in the SMS deposits found in the Exclusive Economic Zones (EEZ) of Papua New Guinea by the deep-sea mining company, Nautilus Minerals Inc. who was recently granted an exploration licence, as well as mining leases (http://www.nautilusminerals.com/). Three other companies (KORDI, Bluewater Metals and Neptune Minerals) are also exploring Seafloor Massive Sulphide (SMS) deposits in the southwest Pacific Ocean. The parliament of the Kingdom of Tonga recently passed the Seabed Minerals Act to regulate mineral exploration and potential mining in Tongan waters. Furthermore, China and Russia have recently submitted applications for exploration of the southwest Indian ridge and the Mid-Atlantic Ridge, respectively (Van Dover, 2011). Thus, largely depending upon whether Nautilus Minerals can successfully bring metals from the seafloor, deep-sea mining will not be limited to territorial waters but eventually spread to areas beyond national jurisdictions.

To date, no commercial SMS mining activity has occurred anywhere in the world. Therefore, the impact of deep-sea mining remains to be evaluated and will inevitably depend on the target resource, its associated ecosystems, and the technology used to extract the ore. Nevertheless, the potential impacts of deep-sea mining have already been listed and are predicted to occur across all marine environments (benthic, bathypelagic, mesopelagic and epipelagic) ranging from local to regional scale over both short and prolonged time scales (Boschen et al., 2013; Gwyther, 2008; Van Dover, 2011). Potential impacts from mining SMS include the physical destruction of the mined sites and their fauna, production of considerable near-bottom, mid-water and near-surface sediment plumes, alteration in hydrothermal circulation at the active sites, waste-water and potential chemical pollution from equipment failure (Gwyther, 2008). With regards to the toxicity of these plumes, it is thought that high concentrations of heavy metals will pose minimal risk to the fauna adapted to active SMS deposits but highly toxic to the general benthic, bathypelagic, mesopelagic and epipelagic fauna (Boschen et al., 2013). Currently, Nautilus Minerals is considering exploiting only extinct black smokers for safety and ecological reasons. However, active vent sites are generally located close to extinct sites to be immune to impacts by mining activities. There is therefore an urgent need to assess the nature and scales of the potential impacts of mining, and how they will affect deep-sea ecosystems.

CO_2 sequestration

With international concern over the increase of CO_2 levels in the atmosphere, different methods for the long term disposal of greenhouse gases are being considered. Notably, sub-seabed and surface seabed disposal of greenhouse gases has been proposed as a solution for reducing excess CO_2 levels in the atmosphere (Stephens and Van der Zwaan, 2005). This method is already in use in the North Sea and in the Barents Sea, where CO_2 has been stored at a depth of 1000 m and 320 m below the seafloor, respectively (Ramirez-Llodra et al., 2011). Although this methods has proven to be safe and efficient (no leakage have been reported), there are many technical challenges that remains to be solved before global CO_2 emissions could be sequestered below the deep-sea floor (Caldeira & Wickett 2002). Another simpler and cheaper method of CO_2 sequestration is the direct disposal of liquid CO_2 onto the seabed (Brewer et al., 1999). However, there is evidence for substantial negative impacts on the fauna and further research is necessary in order to mitigate its effects (Seibel and Walsh, 2003; Tamburri et al., 2000). Indeed, the application of such method will eventually produce carbon dioxide-rich seawater that would spread over the sediment, altering the pH to levels as low as 4.0 near pools of liquid CO_2 (Thistle et al., 2005). Deep-sea organisms are poorly fitted to overcome prolonged elevations in CO_2 and low pH, with capacities 10–100 times lower than comparable shallow-living species (Seibel and Walsh, 2003). This is because deep-sea fauna experience much less environmental variability than do shallow water animals (Shirayama, 1997).

Experiments on the survival of meiobenthos exposed to liquid CO_2 showed that most organisms cannot tolerate the resulting low pH levels of the water (Barry et al., 2005; Barry et al., 2004; Thistle et al., 2005; Thistle et al., 2007). Long exposure to elevated CO_2 levels revealed also to be lethal to most macrofauna and megafauna (i.e. gastropods, echinoids, holothurians, cephalopods and fish) (Barry et al., 2013). Despite evidences demonstrating important environmental impacts caused by deep-sea CO_2 disposal, the US Department of Energy seeks to sequester 1 gigatonne of carbon per year by 2025 (US DOE, 1999) and other countries such as Japan are also seriously considering substantial deep-sea CO_2 sequestration (Yamasaki, 2003). Therefore, along with marine litter, deep-sea CO_2 disposal will possibly become the most significant threat to the deep sea.

Other important threats

Another important human-induced threat to deep-sea ecosystems is climate change, which includes all of the associated consequences of increased CO_2 levels in the atmosphere, such as ocean acidification, temperature change and the expansion of hypoxic zones. Previously, the deep sea was thought not to be affected by the effects of surface-driven cycles and impacts (Menzies, 1965), but there is an increasing amount of research that showed large scale surface environmental changes to directly affect the functioning of deep-sea ecosystems (Danovaro et al., 2004; Jones et al., 2014; Kaiser and Barnes, 2008; Smith et al., 2008). Changes in surface productivity and environmental variables such as temperature or salinity have been shown to influence deep-sea species distribution, abundance and behaviour (Levin et al., 2001; Ruhl and Smith, 2004). Increasing surface temperatures can also affect the formation of cold oxygenated deep water, amplifying the existing formation of Oxygen Minimum Zone (OMZs) in the deep sea (Helly and Levin, 2004). Expansion of OMZs will undoubtedly alter the composition, diversity and functional properties of bathyal ecosystems (Hofmann et al., 2011). For the majority of species that are not tolerant to hypoxia, increased OMZs will alter their spatial distribution (Guilini et al., 2012). On the other hand, some species (e.g. squid or jellyfish) might benefit from lower-oxygen ocean and expand their distribution ranges both vertically and horizontally (Zeidberg and Robison, 2007), altering overall community composition.

The next major consequence of increased atmospheric CO_2 is a decreased pH of seawater. The ocean, being a natural sink for CO_2, absorbs most of the anthropogenic CO_2 released in the atmosphere, causing ocean acidification (Kleypas et al., 1999). This change in the overall pH of seawater has some profound implications for calcifying fauna (Gattuso et al., 1999). For example, the distribution of cold-water corals already reflects the acidic conditions in the North Pacific (Guinotte et al., 2003) but if CO_2 levels keeps on increasing, entire cold-water coral habitats could disappear. All these environmental changes do not occur in isolation, but will co-occur and interact with each other. The severities of cumulative impacts are hard to predict and should be a research priority to fully understand the threats of climate change for the deep sea.

Bioprospecting for biological and genetic materials of potential commercial interest has been increasing significantly (Synnes, 2007). In the deep sea, such bioprospecting is in its infancy, but some interesting research has revealed possible antifungals, anti-cancer products and skin protection products based on marine organisms (Molinski et al., 2009). The impacts of such activity will be highly dependent on the scale of the extractions. In addition, some sparse localised activities, such as the deep-water sewage dumpsite along the eastern seaboard of the United States (2500 m) that was used for the disposal of industrial and municipal wastes from 1972 until 1992 (Grassle and Maciolek, 1992; Lonsdale, 1977; Rex and Etter, 2010; Smith et al., 1996; Snelgrove and Smith, 2002) or the laying of underwater cables have negative impacts on the deep-sea floor. Such impacts are comparable in type, but not in persistence, spatial scale or magnitude of the disturbance created to that caused by industrial removal of seafloor resources and thus, are not considered as a major concern (Ramirez-Llodra et al., 2011). However, these activities, poses additional pressure to the deep oceans, which are already subject to a large amount of disturbance.

The deep sea; a vulnerable ecosystem in need of protection

Similarly to the spread of human activities into deep waters, new technologies rapidly allowed marine scientists to explore the deep ocean to quickly realize that it was much more biologically diverse and dynamic than originally thought (Gage and Tyler, 1991). It did not take long to understand that deep-sea species and habitats were intrinsically more vulnerable and less resilient than their shallow-water counter parts (Grassle, 1977; Holling et al., 1995). Reduced rates of growth, respiration, reproduction, and recruitment are common characteristics of organisms inhabiting the deep sea (Freiwald et al., 2004; Gage and Tyler, 1991; Roberts et al., 2006; Tyler et al., 1982). This implies that most deep-sea organisms have reduced resilience and thus are highly vulnerable to anthropogenic activities.

The text book example of the vulnerability of deep-sea organisms to intense and unmanaged exploitation in deep-sea fauna is the case of fish. Typical life histories of deep-sea fish make them particularly vulnerable to overfishing and numerous examples of fisheries can illustrate such low resilience. The orange roughy (*Hoplostethus atlanticus*), a slow growing fish that reaches ages exceeding 100 years and known to aggregate in large numbers around seamounts during feeding and spawning, is one of the most highly marketable deep-sea fish that is subject to intense fisheries worldwide (Hilborn et al., 2006). The life-history characteristics of the orange roughy, together with a lack of deep-sea fisheries management leaded to a "boom and bust" cycle that has characterized many other individual fisheries (Norse et al., 2012). This happens when the biomass of the previously unfished stocks is fished down rapidly (often within 5–10 years), to the point of commercial extinction or very low levels. With reduced growth rate and late reproduction, stock recovery is a timely process, spanning several decades (Roberts, 2002).

Other deep-sea organisms, such as cold-water corals, have life history characteristics sometimes far more extreme than deep-sea fish, making them much equally or much more vulnerable to anthropogenic disturbances. Some cold-water corals have growth rates <1 mm per year with life span exceeding 1000 years (Carreiro-Silva et al., 2013; Roark et al., 2009; Roark et al., 2006; Roark et al., 2005). Therefore, recovery of cold-water coral assemblages from fishing disturbance occurs extremely slowly. Even after fishing has ceased for 5–10 years no signs of faunal recovery have been reported (Althaus et al., 2009; Williams et al., 2010).

In addition to the life history characteristics, related to the slow pace of life in the deep sea, our lack of knowledge on many aspects of the deep ocean increases the vulnerability of deep-sea habitats and organisms to anthropogenic activities. The deep sea is considered as one of the "least understood" environments on earth because of the vast area (64 percent of the Earth's surface lies more than 200 metres below sea level) and the relatively small amount of scientific activity in our oceans (Ramirez-Llodra et al., 2010; Rogers et al., 2008). Only about 0.0001 percent of the deep-sea floor has been subject to biological investigation (UNEP, 2007). This implies that our knowledge of the deep sea has tended to lag behind the development of anthropogenic activities, and significant impacts often have occurred before they could have been anticipated. Detailed spatial information is lacking for much of the deep sea with new habitat-types still being discovered (Ramirez-Llodra et al., 2010).

In recognition of the vulnerability of deep-sea biodiversity, the United Nations General Assembly (UNGA), within the framework of the United Nations Convention on the Law of the Sea, called upon relevant intergovernmental organizations "to urgently identify ways to integrate and improve, on a scientific basis, the management of risks to marine biodiversity of seamounts and certain other underwater features". In 2006, the formulation of the UNGA Resolution 61/105 (UNGA, 2007) called on Regional Fisheries Management Organisations (RFMOs) to identify areas where these habitats occur, or are likely to occur, and act to prevent significant adverse impacts. This was further guided by an international consultative process set by the Food and Agriculture Organisation (FAO) to provide the recommendations and management guidelines (FAO, 2009). Whilst some RFMOs had taken significant steps, a lack of scientific information on the distribution of VMEs hampered the application of protective measures in the majority of areas (Weaver et al., 2011). It is widely acknowledged that the effective management and protection of deep-sea ecosystems will require the implementation of significantly larger marine spatial planning, research and restoration programs than what has been done so far (Barbier et al., 2014; Mengerink et al., 2014).

Objectives and thesis outline

This thesis intends to contribute towards a better understanding of some human impacts on deep-sea habitats surrounding the Azores archipelago. Located in the middle of the Atlantic Ocean, the Azores has an extensive Economic Exclusive Zone (EEZ) of almost 1 million square kilometres, most of it being below 200 meters. The marine region harbours many deep-sea Vulnerable Marine Ecosystems (cold-water corals, sponge fields and hydrothermal vents) believed to be of great ecological and economical value. Therefore, the Azores is a perfect case study site to evaluate the impacts of human activities on deep-sea ecosystems. Specifically, the information obtained during the study aims to provide baseline information on the impacts of fishing and litter in the deep sea, which will help assist the development of management tools for minimising significant adverse impacts and promote conservation of deep-sea habitats. In addition, it evaluates the ecological importance of Vulnerable Marine Ecosystems for deep-sea fauna to further assess the value of these ecosystems and potential cascading effects of such unmanaged threats. The thesis is composed of four research based chapters:

Chapter I Any analysis of the impacts of fishing on the deep sea, necessitates accurate information that documents the extraction of deep-sea marine resources. Data sources such as those provided by national fisheries statistics are useful but have many limitations. Official landings generally lack taxonomic resolution in early years and provide no information on non-target species (i.e. bycatch) and other extractive activities not mandated to report their catch (i.e. recreational fishing). Therefore, the use of official statistics does not permit a complete picture on the level of resource extraction and impede describing changes in fisherman behaviour, such as the expansion towards deep-sea fishing grounds. In addition, reconstructed catch time series are essential for the development of reliable ecosystem models that are being developed for the management of marine resources. The aim of this chapter is to estimate total catches of deep-sea resources (along with all other fisheries) that occur within the Azorean territory.

Chapter II As opposed to most deep-sea fisheries occurring in the high Seas, the deep-sea fishery off the Azores has been considered as an example of sustainable fishing (Koslow et al., 2000; Norse et al., 2012). Central to this view is the use of deep-sea longlines and handlines to catch demersal fish instead of bottom trawling, a gear currently prohibited in the region. Bottom trawls is considered a highly destructive fishing technique and is one of the main reasons deep-sea fishing in the high seas is considered to be unsustainable. Although the use of deep-sea longlines is considered to have little impact on deep-sea habitats, this remains to be demonstrated. The objective of this chapter is to provide a quantitative analysis of the impact of deep-water longline on epibenthic organisms and compare its effect with bottom trawling.

Chapter III Vulnerable Marine Ecosystems (VMEs) are increasingly at risk from destructing fishing practices. Yet, there is mounting evidence that they play an important ecological role as habitats for a wide variety of deep-sea fauna, including species of commercial interest. Understanding the services provided by these habitats will better assess the long-term impacts of anthropogenic activities on the deep sea. The objective of this chapter is to assess the importance of Vulnerable Marine Ecosystems for some demersal fish species that would help to anticipate potential long term impacts of anthropogenic activities for marine systems as a whole.

Chapter IV Marine litter is an emerging pollution issue that has gained much interest by the scientific community over the past decade. The problem of marine litter on shallow water and coastal ecosystems has been well described, but little is known on its distribution and impacts in deep-sea ecosystems. The aim of this chapter is to assess marine litter distribution at two different spatial scales by understanding its sources and potential impacts: on a deep-sea Vulnerable Marine Ecosystem in the Azores; and at a larger scale in the North East Atlantic and Mediterranean sea. In addition, I provide a comparative analysis of the litter densities in the VMEs of the Azores with many other deep-sea locations in Europe.

The chapters of this thesis were based on the following manuscripts:

Chapter I
Pham, C. K., Canha A., Diogo H., Pereira J.G., Prieto R., & T. Mortato (2013). Total marine fishery catch for the Azores (1950-2010). *ICES J. Mar. Sci*. 70, 564-577.
DOI: 10.1093/icesjms/fst024

Chapter II
Pham C.K., Diogo H., Menezes G., Porteiro F., Braga-Henriques A., Vandeperre F., & T. Morato. (2014). Regulated bottom longline helps achieving sustainability of deep-sea fisheries. *Sci. Rep.* 4:4837.
DOI: 10.1038/srep04837

Chapter III
Pham C.K., Vandeperre, F., Menezes, G., Porteiro, F., Isidro, E., T. Morato. In press. The importance of deep-sea Vulnerable Marine Ecosystems (VMEs) for demersal fish in the Azores. *Deep Sea Res. Part I Top. Stud. Oceanogr*

Chapter IV
Pham C.K., Gomes-Pereira J.N., Isidro E.J., Santos R.S., & Morato T (2013) Abundance of litter on Condor seamount (Azores, Portugal, Northeast Atlantic). *Deep Sea Res. Part II Top. Stud. Oceanogr.*98: 204-208.
DOI: 10.1016/j.dsr2.2013.01.011

Pham C.K., Ramirez-Llodra E., Alt CHS., Amaro T., Bergmann M., Canals M., Company J.N., Davies J., Duineveld G., Galgani F, Howell K.L., Huvenne VAI., Isidro E., Jones D.O.B., Lastras G., Morato T., Gomes-Pereira J.N., Purser A., Stewart H.,Tojeira I., Tubau X., Rooij D. & P.A., Tyler (2014) Marine litter distribution and abundance in European Seas, from the shelf to deep basins. *PLoS ONE*. 9(4): e95839.
DOI:10.1371/journal.pone.0095839