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# **Review of parasites, pathogens and contaminants of deep sea fish with a focus on their role in population health and structure.**

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## **1. Introduction**

This review provides a summary of the parasites, pathogens and contaminant related impacts on deep sea fish normally found at depths greater than about 200m. There is a clear focus on worldwide commercial species but has an emphasis on records and reports from the north east Atlantic. In particular, the focus of species following discussion were as follows: deep-water squalid sharks (e.g. *Centrophorus squamosus* and *Centroscymnus coelolepis*), black scabbardfish (*Aphanopus carbo*) (except in ICES area IX – fielded by Portuguese), roundnose grenadier (*Coryphaenoides rupestris*), orange roughy (*Hoplostethus atlanticus*), blue ling (*Molva dypterygia*), torsk (*Brosme brosme*), greater silver smelt (*Argentina silus*), Greenland halibut (*Reinhardtius hippoglossoides*), deep-sea redfish (*Sebastes mentella*), alfonsino (*Beryx* spp.), red blackspot seabream (*Pagellus bogaraveo*). However, it should be noted that in some cases no disease or contaminant data exists for these species. Where appropriate, bathymetric data was based on definitions provided by Bray *et al.* (1999) and Bray (2004).

Studies of diseases and parasites of deep sea fish are in their infancy and records are scarce compared with economically and ecologically important species from shallower waters. Furthermore, most studies have been carried out in the northern hemisphere. Reports of parasites, pathogens and diseases of deep water fish generally consist of faunistic studies; in some cases this can be limited due to a lack of taxonomic expertise in selected parasite groups. Klimpel *et al.* (2001) suggested that studies on deep water fish parasites (and pathogens) was limited because of logistic constraints, limited numbers of fish being caught and the conflicting requirements of different disciplines.

It has been estimated that deep water fish have an average of 1.5 metazoan parasites per fish species. In this context, metazoans comprise Myxozoa, Monogenea, Digenea, Cestoda, Acanthocephala, Nematoda, Hirudinea and Copepoda. Inclusion of protistans, bacteria and viruses will clearly increase this number greatly. With around 13,500 fish species occurring at depths greater than 200m, it can be surmised that somewhere between 20,000 to 43,000 different parasite species may occur on deep water fish; to date only around 600 deep water parasites have been identified or recorded (Klimpel *et al.*, 2001). Almost half of the parasites reported from deep water fish are Digenea, with copepods, cestodes and Monogenea making up the other half; the remaining small number of species are represented by the other major parasitic groups.

As a general rule, parasite diversity decreases with depth partly due to decreases in biomass in the pelagic zone, leading to reduced prey availability and thus limiting transmission for those parasite requiring intermediate hosts. Marcogliese (2002) suggested that parasite species richness and intensity of infection are highest in epipelagic and benthic zones, decrease in vertically migrating mesopelagics and are lowest in deep non-migratory mesopelagic and bathypelagic fish. Furthermore, mesopelagic and bathypelagic fish have impoverished parasite communities compared with benthic fish, which possess a more diverse helminth parasite fauna (Marcogliese, 2002).

## 2. Taxonomic review

This includes, where possible, an overview of the major types, lifecycle patterns, general distribution and any pathology recorded directly with those in deep sea hosts. It cannot be exhaustive given the time constraints.

### 2.1 Viruses

There is substantial literature on the viral fauna of deep sea sediments but there are no reports of viral pathogens in deep sea fish species. These will certainly occur and are likely to be involved in disease occurrence. It is highly likely that lymphocystis disease, caused by an iridovirus will affect deep sea species but the disease is usually superficial and has not been associated with fish mortalities. This is an area of scientific interest but without significant sampling effort viral infections are unlikely to be detected bearing in mind the requirement for fresh material, ideally not frozen.

### 2.2 Bacteria

As for section 2.1 above. Bacterial pathogens have not been reported from deep sea fish.

### 2.3 Fungi (including Microsporidia)

Microsporean parasites are extremely common in fish and are agents of significant disease conditions in freshwater and marine environments. Most fish species are susceptible to these pathogens (which are now classified amongst the fungal kingdom). There are however, only few records of microsporean parasites in deep sea fish. Lom *et al.* (1980) recorded the presence of *Pleistophora duodecimae* in the musculature of the rat-tail *Coryphaenoides nasutus* and *Glugea capverdensis* in the intestine, mesentery and ovary of the lantern fish (*Myctophum punctatum*) from the Atlantic Ocean. The former induced enlarged muscle fibres within which the parasite developmental stages and spores has replaced the muscle. Only one fish out of 15 examined harboured the infection. This suggests that this parasite may be over dispersed in the population with a few individuals expressing significant disease. The infection with *G. punctatum* in lantern fish was detected in a single specimen. Typical of infections with this genus the infection presented as numerous round or oval xenomas (parasite cysts) up to 2mm in diameter in the intestinal wall. Presumptive

secondary xenomas were found in the ovary. Given the large number of microsporean parasites known and the wide range of fish species affected it is surprising that additional microsporean species have not been recorded from deep sea fish species.

True fungal pathogens possessing hyphae have not been recorded from deep sea fishes. However, the well known fungal-like pathogen *Ichthyophonus* (Mesomycetozoea) has been recorded in the liver of *Scopelogadus beanii* (Gunther) from the Atlantic Ocean (Gartner & Zwerner, 1988). Diseased fish revealed cysts up to 20mm in diameter in 4 out of 400 fish examined. Histologically, the infection resulted in significant necrosis of the liver. It was noted that fish from the western Atlantic and the slope waters of the mid-Atlantic Bight showed a higher prevalence of infection than in fish from other areas. Based on the observed pathogenicity of the infection the authors suggested that the infection could result in loss of reproductively competent individuals. *Ichthyophonus* can occur at very high prevalence in other fish species and the infection in herring stocks from the North Sea was associated with population declines (Møllergaard & Spanggaard, 1997). It is highly likely that *Ichthyophonus* is a pathogen of other deep sea fish and efforts should be taken to investigate for this.

#### 2.4 Protista

Protistan parasites appear to be under represented in deep sea fish species taking into account their abundance and diversity in marine species from coastal shelf waters and in freshwater environments. This is almost certainly not to be the case and is a reflection of the logistic difficulties in obtaining material and funding to support the research. There are a few reports of protistan taxa that occur in deep water species. Coccidiosis caused by *Eimeria jadvigae* has been reported in *Coryphaenoides holotrachys* from waters off the Falkland Islands in the southern Atlantic Ocean (Grabda, 1983). Infections in the swim bladder were detected in 80-100% of the populations examined. Pathological changes were noted in the swim bladders and comprised of extensive thickening and loss of structure to the organ. Parasite stages were present throughout the tissues with spores being present at all levels. The organ was effectively rendered non-functional by the infection. This example demonstrates the capacity for these organisms to induce significant

pathological changes in their hosts, sufficient to compromise normal biological functioning. Surprisingly, electronic searches did not reveal any reports on other protistan taxa affecting bathymetric fish species. Further investigations are needed to ascertain the diversity and prevalence of these infections in deep sea fish species.

## 2.5 Myxozoa

Parasites of the phylum Myxozoa are common in fish and are the causative agents of several economically important diseases in aquaculture systems and wild stocks. They are highly specialised metazoans with complex life cycles, characterised by the formation of multicellular spores with polar capsules and extrudible polar filaments. Increasingly, there is evidence that these and other myxozoan pathogens can have a significant effect on wild fish populations. In marine fish, myxosporeans (and other parasites) have been proposed as useful tags for stock discrimination on the basis that these provide useful indications on ecologically discrete populations rather than purely genetic stocks (see 3.1 below).

In contrast to the protistan and prokaryotic organisms considered in the preceding section, there are a number of studies which have examined deep sea fish for the presence of myxosporeans, although few in the North Atlantic region. However, in combination they account for only 17% of parasite records (Bray, 2004). Several families of myxozoan parasites have been described in deep sea fish, amongst these are Myxobolidae, Parvicapsula, Sphaeromyxa, Auerbachidae, Alatosporidae, Ceratomyxidae and Myxidiidae. Most of these are coelozic i.e. living in body cavities such as the gall bladder, renal tubules and urinary bladder. Others, including the myxobolids are histozoic, residing within tissues. However, both groups have extrasporogonic developmental stages that may elicit a host response resulting in significant pathology and compromise the ability of affected fish to function normally. Reports from the rock grenadier (*Coryphaenoides rupestris*) in the North Atlantic include *Myxidium coryphaenoidium* (Yoshino & Noble, 1972; Moser *et al.*, 1976), *Myxidium* species, *Zschokkella hildae* and *Auerbachia pulchra* (Zubchenko, 1975, 1981; Zubchenko & Krasin, 1980). Additional reports of Myxosporea infections were provided by Alioshkina *et al.* (1985) who examined *Beryx* sp. from the Whale Ridge (Northern Atlantic). In none of these cases were assessments on parasite pathogenicity undertaken. A series of reports by Moser (1976 a & b), Moser & Noble

(1975, 1976 a & b, 1977 a, b & c) and Moser *et al.* (1976) detected a variety of myxosporean parasites in macrourids, sablefish (*Anoplopoma fimbria*) *Sebastes* sp. and rattails (*C. pectoralis*) in deep water off the Californian coast, again no information on pathogenicity was provided. Despite the lack of information on these parasites as agents of disease, numerous examples are present in the literature and many species are a major problem in aquaculture of marine fish species as well as causing significant detrimental effects on the flesh quality of several valuable species whereby muscle necrosis and liquefaction results from infections with *Kudoa* and *Unicapsula* spp. It is not known whether members of either of these genera exist in deep sea fish species but it is likely.

## 2.6 Monogenea

Monogenea typically occur on external surfaces of fish hosts, in particular on the fins, skin and gills, and in some cases with a very restricted niche on their respective hosts. A small number have successfully adapted to living inside their hosts and have been found within the urinary bladder, within the visceral cavity and within the gut (Alvarez *et al.*, 2006; Bilong Bilong *et al.*, 1994; Bilong-Bilong *et al.*, 1996; du Preez *et al.*, 2007). Monogenea are classified into two major groups, the Monopisthocotylea which possess small hooks and typically feed on skin and mucus and the Polyopisthocotylea which are larger, possess clamps and feed on blood. Monogeneans are viviparous or ovoviviparous, and have direct lifecycles. It has been estimated that around 70 species of Monogenea occur on deep water fish (Klimpel *et al.*, 2001). However, given that estimates of the number of Monogenea currently is somewhere around 25,000 (Whittington, 1998), it is likely that reports and descriptions of Monogenea associated with deep sea fish is likely to increase. Furthermore, deep water monogeneans are distantly related to shallower water forms and are considered to be archaic (Rohde, 1988). No pathological changes associated with monogenean infections in deep sea fish have been reported, although it is known that monogeneans can cause pathology as a result of feeding and movement activities on the host.

The majority of monogeneans reported from deep water fish are relatively host-specific and are from the monogenean families Monocotylidae (5 spp.), Acanthocotylidae (1 sp.), Capsalidae (9 spp.), Gyrodactylidae (2 spp.),

Tetraonchoididae (3 spp.), Dactylogyridae (3 spp.), Hexabothriidae (5 spp.), Plectanocotylidae (2 spp.), Mazocraeidae (2 spp.), Anthocotylidae (1 sp.), Discocotylidae (4 spp.), Heteraxinidae (1 sp.), Microcotylidae (5 spp.), Dicliphoridae (39 spp.) and Microbothriidae (1 sp.).

In most cases where deep sea fish have been examined, monogeneans have been found, although in some cases these have not been identified to species. For example, Karlsbakk *et al.* (2002) examined *Hydrolagus affinis* from depths of between 1300 and 2100m off Greenland and found two monogenean species. One they identified to genus; the other was only identified to family. Macrourids are hosts to monogeneans, *Macrouridophora macruri* being reported on the gills of 20% of *Macrourus berglax* caught in water depths of around 300m in the Greenland sea (Klimpel *et al.*, 2006); *Coryphaenoides brevibarbis*, caught at depths of around 2500m and *Albatrossia pectoralis* are hosts for *Cyclocotylodes* spp. (Kritsky and Klimpel, 2007). Whilst only two species have been described within the genus *Cyclocotylodes*, Kritsky and Klimpel (2007) consider that several undescribed species may exist in deep water hosts. Fish within the family Chimaeridae are hosts for polyopisthocotyleans of the *Callorhynchocotyle* and *Chimaericola* spp. (Kitamura *et al.*, 2006; Pascoe, 1987). In addition, *Centropomus nigrescens* from the Pacific coast of Mexico is host to the diplectanid *Cornutohaptor nigrescensi* (Mendoza-Franco *et al.*, 2006). A large scale survey of fish from the Rockall Trough at depths of around 1000m was conducted by Pascoe (1987) who showed that prevalences ranged from around 5% to 100% for different monogenean species in a range of hosts, including *Coryphaenoides* spp and *Aphanopus carbo*. Only 8 species of host out of 36 species examined were found to be infected. However, for hosts deemed negative, only low numbers of fish were examined, ranging from 1 to 12 (mean of 3 fish per species examined). In addition, in depth studies were only conducted on those hosts deemed positive following an initial cursory screen of skin and gills. Thus it is possible that Pascoe (1987) provides underestimates of the diversity of monogeneans in the Rockall Trough. No information was provided on pathology of these parasites, although overall low numbers of parasites were found on individual hosts and thus are unlikely to have been considered detrimental to host survival.

Munroe *et al.* (1981) described *Dicliphora nezumiae* from the macrourid fish *Nezumia bairdii* and showed that whilst the parasite occurred throughout the depth

range of capture (300-1900m), intensity and prevalence of infection was greater at depths of 700-1000m. They considered that this was due to the high density of hosts occurring in this depth range, which corresponds to the mid-range of depths at which *N. bairdii* occurs. Host size had limited impact on parasite densities which occurred preferentially on the filaments of the first gill arch.

In a review of monogeneans from deepwater fish in south-eastern Australia, Rohde (1988) and Rohde and Williams (1987) showed that the fauna of Monogenea was depauperate compared with shallow water counterparts, a feature matched with deepwater hosts in the north Atlantic. Of the 67 species of fish examined, only 16 species of Monogenea were found, and of these only 7 monogeneans could be accurately identified to species (Rohde and Williams, 1987), emphasising the lack of taxonomic rigour in studies of this nature and the need for continued and in-depth studies of the taxonomy of this important group of parasites.

## 2.7 Digenea

Digenea, or trematodes, have been extensively studied in deepwater fish, in part due to the efforts of a small group of researchers with a specialism in this field with ready access to intestinal contents of fish (the predominant organ infected with digeneans). In general the lifecycle of digeneans involves one or two invertebrate hosts, a vertebrate host (in the aquatic environment this tends to be fish) and a final vertebrate host in which sexual reproduction takes place. However, to date no complete lifecycles of deep-water digeneans have been elucidated, due to the technically demanding needs of experimental approaches required to complete lifecycles in the laboratory, although theoretical lifecycles have been inferred from survey data. Digeneans have been recorded in most species of fish examined and recent studies have led to the discovery of new species and genera (Blend *et al.*, 2000; Blend *et al.*, 2004; Bray, 1990; Bray and Campbell, 1995; Bray and Gibson, 1991; Bray and Gibson, 1998; Campbell, 1975; Lumb *et al.*, 1993; Palm *et al.*, 1998; Pardo-Gandarillas *et al.*, 2008). It has been estimated that approximately 300 species of Digenea have been reported from deep-water fish to date, but given the high diversity and relative frequency at which new species are reported, this figure is likely to increase (Klimpel *et al.*, 2001). Bray *et al.* (1999) in reviewing the phylogeny of deep-water digeneans suggested that they were derived from continental shelf

forms and that some host-switching may have occurred. Furthermore, they were able to show that there was a lack of zoned depth-related digenean community structure. Bray *et al.* (1999) suggested that only 18 families (out of 60 known in fish) of digeneans occurred in deep-waters and that whilst little is known about digeneans in deep-sea areas, nothing at all was known about the diversity of digeneans in trenches and mid-ocean ridges systems. In common with other parasite groups, most studies of digeneans tend to be of a faunistic nature and thus few papers exist on pathology associated with deep-water digeneans. It is likely that those occurring in coelozoic positions in the host will have limited impact on host survival; those occupying a histozoic position are more likely to elicit a pathological response although this remains to be tested.

## 2.8 Cestoda

Tapeworms exist in both freshwater and marine fish species but are generally found at low prevalence and low intensity in most hosts. Few pathogenic species occur although it is known that heavy burdens of cestodes can lead to occlusion of the gut, poor food assimilation, and in some cases, death. As with several other parasite groups, little attention has been paid to the taxonomy of deep sea cestodes, reflecting a lack of taxonomic expertise in this important group of fish parasites. Lifecycles of cestodes are generally relatively simple, usually involving an arthropod and one or two vertebrates as intermediate and final host. In marine systems, elasmobranchs tend to act as a final host for cestodes. However, no complete lifecycles of cestodes associated with deep sea fish have been elucidated to date.

It is likely that as more fish are examined specifically for the presence of cestodes (or other parasites), new genera and species will be uncovered. For example, in examining *Squalus melanurus* and an unidentified *Centrophorus* sp. from deep water off New Caledonia, Beveridge and Justine (2006) described two new genera of trypanorhynch cestodes, four new species of cestodes, plus provided a new host record for another previously described cestode; examination of shortfin spine eel *Notacanthus bonaparte* from the northeast Atlantic resulted in the description of a new genus and species of pseudophyllidean cestode, *Bathycestus brayi* (Kuchta and Scholz, 2004); a new genus and species of pseudophyllidean (*Australicola pectinatus*) was described from *Beryx splendent* from the Pacific coast of Tasmania,

to add to the other two species of cestodes previously reported from this species (Kuchta and Scholz, 2006). Other new species reported in deep sea fish include an unidentified bothriocephalid from *Bathylagus euryops* caught at the mid Atlantic Ridge at depths of between 2500 and 3000m (Busch *et al.*, 2008) and *Probothriocephalus alaini* from the intestine of *Xenodermichthys copei* (Alepocephalidae) from the North Atlantic (Scholz and Bray, 2001). Typically, *Grillotia* spp., tetraphyllidean and pseudophyllidean plerocercoids are reported in deep sea hosts (Brickle *et al.*, 2006; Kellermanns *et al.*, 2009; Klimpel *et al.*, 2007; Klimpel *et al.*, 2008; Lester *et al.*, 1988; Palm and Klimpel, 2008; Palm and Schröder, 2001; Walter *et al.*, 2002).

Members of a primitive cestode order (Gyrocotylidae), have been reported in *Chimaera* spp. and *Hydrolagus* spp. *Gyrocotyle* spp. appear to be host and site specific, normally occurring in the anterior tier of the spiral valve (Halvorsen and Williams, 1967). Whilst intense infections with larval stages occur, the parasite populations are regulated by intrinsic factors within the parasite until only two adult stages remain. Although not explicitly described by Halvorsen and Williams (1967), attachment of the parasite to the spiral valve wall elicits a minor host response.

### 2.9 Acanthocephala

The Acanthocephala are a minor group of parasites that are closely allied to the rotifers. Typically, they possess a spiny proboscis which gives rise to their common name of spiny headed worms. The sexes are separate and lifecycles are complex, usually involving at least three hosts, including an invertebrate (normally an arthropod), a teleost host and a mammalian or bird host in which sexually mature adults mate and release eggs into the environment. In addition, numerous hosts can act as paratenic (transport) hosts in which no development takes place. Within the fish host, Acanthocephala are normally found attached via the proboscis to the intestinal lining or encysted within the viscera. Pathology associated with acanthocephalans can be variable, ranging from minimal or no impact through to penetration of the intestinal wall by the proboscis or encapsulation of parasites by a host response. It is recognised that some acanthocephalans can alter host behaviour to maximise transmission to the next host (Baldauf *et al.*, 2007; Cornet *et al.*, 2009; Médoc *et al.*, 2006; Tain *et al.*, 2007).

Records of acanthocephalans in deep sea fish worldwide are sparse, with the majority of records from Antarctic and sub-Antarctic fishes. This in part reflects the efforts of a small number of researchers to categorise parasites in these areas rather than a true representation of the distribution of these parasites (Campbell *et al.*, 1980). Unusually, Zdzitowiecki (1996) provided depth data following a survey of fish for their acanthocephalan burdens. Acanthocephalans were recorded in fishes at depths in excess of 1540m. Brickle *et al.* (2006) in considering parasites as tags for the Patagonian toothfish (*Dissostichus eleginoides*) around the Falkland Islands, reported on the presence of larval *Corynosoma bullosum*, which has been reported in a number of other hosts, including *Notothenia coriiceps* and *Macrourus whitsoni* (Edmonds, 1954; Klimpel *et al.*, 2006; Palm *et al.*, 1998; Walter *et al.*, 2002). Zdzitowiecki (1986) considered that this parasite predominately occurred in fish collected below 100m in the Antarctic. Whilst no comment has been made on any pathology associated with this parasite by any authors, it is likely that this parasite has minimal impact on the host. Similarly, the presence of *Hypoechinorhynchus thermaceri* from the abyssal zoarcid *Thermaceres andersoni* from the eastern Pacific at 2650m was described with the absence of any pathological data (de Buron, 1988).

At least ten species of *Echinorhynchus* have been recorded from deep water fish, including *E. brayi* from *Pachycara crassiceps* (Zoarcidae) from the Porcupine Seabight, Northeast Atlantic (Wayland *et al.*, 1999) and *E. longiproboscis* from the intestines of *D. eleginoides* and *Macrourus holotracy*s from the Falkland Islands (Rodjuk, 1986). Some of these records will need to be reassessed in the light of new understandings of the genetic relationships of this group and new taxonomic criteria used to discriminate species. For example, both *E. gadi* and *E. truttae* have been recorded in the Antarctic and in deep water fish from the north Atlantic respectively (Melendy *et al.*, 2005). However, both are normally parasites of shallow water fish from the north Atlantic.

## 2.10 Nematoda

Nematoda have complex lifecycles, involving at least three hosts. Many nematodes are also able to utilise paratenic hosts to maximise transmission to the final hosts, usually a bird or mammal. Few parasitic nematodes have successfully invaded the deep sea, although a number of genera normally occurring in shallower water, such

as *Pseudoterranova*, *Contraecum* and *Anisakis* are found deep water fish (Alioshkina *et al.*, 1985; Blaylock *et al.*, 2003). Particularly important in view of its potential zoonotic impact is the presence of *Anisakis* spp. in many deep water fish species (Gartner and Zwerner, 1989; Klimpel *et al.*, 2003; Klimpel *et al.*, 2004; Klimpel *et al.*, 2007). Molecular confirmation of the presence of further zoonotic nematodes *Pseudoterranova decipiens* (and *A. simplex*) has been conducted in macrourids collected at depths of approximately 400m around Greenland (Kellermanns *et al.*, 2007). *Coryphaenoides mediterraneus* collected at depths of between 1700 and 3500m from the Charlie-Gibbs Fracture Zone on the mid-Atlantic Ridge were found to be infected with *A. simplex* s. l., *Ascarophis longiovata*, *Capillaria* sp., *H. aduncum*, *Neoscarophis longispicula* and *Spinitectus oviflagellis*. *Aniskais* sp. and *Hysterothylacium* sp. have also been recorded in the stomachs of *Halosaurus macrochir* along with a new species of *Comphoronema* from the same geographical zone at depths of between 2500 and 3000m (Klimpel *et al.*, 2008; Moravec and Klimpel, 2007a). *Moravecnema segonzaci* was described from the intestine of *Pachycara thermophilum* (Zoarcidae) caught at a hydrothermal vent at the Mid-Atlantic Ridge, at depths of 3000 to 3500m (Justine *et al.*, 2002). To date this is the only species of parasitic nematode reported from hydrothermal vent fish. Descriptions and redescriptions of nematodes from deep sea fish continue to be made, particularly in light of new expeditions but often as a result of specific taxonomic expertise of individuals (Moravec *et al.*, 2010; Moravec and Klimpel, 2007b; Moravec and Klimpel, 2009). However, limited studies exist on the pathology of these parasites in deep sea fish.

### 2.11 Copepoda and Isopoda

Few species of parasitic copepods have successfully exploited deep water fish. It has been estimated that only about 50 species of parasitic copepods occur on deep water fish (Boxshall, 1998). Deep water parasitic copepods occur mainly in the order Siphonostomatoida and to a lesser extent, within the order Cyclopoida. The genera of parasitic copepods found associated with fish is provided as table 1. In common with other parasitic copepods, all deep water copepods have simple lifecycles, not requiring the use of intermediate hosts. Some parasitic copepods, including members of the Lernaepodidae, Sphyrriidae and Chondracanthidae, show sexual dimorphism, relying on dwarf males that become parasitic on the larger females to

ensure sexual reproduction takes place, limiting the problems associated with finding suitable partners (Østergaard and Boxshall, 2004). Members of the family Pennellidae normally utilise two successive hosts in their lifecycle (Goater and Jepps, 2002; Tirard *et al.*, 1996; Van Damme *et al.*, 1993). However, the pennellid *Sarcotretes scopeli* reported from at least 6 families of deep water fish appears to only use a single host in order to complete its lifecycle (Boxshall, 1998). It has been promulgated that this truncated lifecycle and wide host specificity in pelagic deep water fish may occur as a direct result of the difficulty of finding suitable hosts in deep water. Host specificity of deep water parasitic copepods on demersal hosts is apparently far more restricted.

Unlike copepods, few records for parasitic isopods exist. This is not surprising as it reflects in part a lack of taxonomic expertise in this group which have received only modest attention by parasitologists (Bunkley-Williams and Williams, 1998). The isopod *Syscenus infelix* (Aegidae) has been reported from macrourid hosts, particularly *Nezumia* spp. from the western north Atlantic and in the Mediterranean at depths of between 400 and 2000m (Kensley and Cartes, 2003; Ross *et al.*, 2001). The blind isopod attaches to the dorsal midline immediately behind the first dorsal fin, with apparently only a single isopod per fish. At the attachment site, a characteristic depression is formed as a result of feeding on scales and tissues of the host (Kensley and Cartes, 2003). Three further isopods from the family Aegidae, *Aega angustata*, *A. cf. deshaysiana* and *A. webbii* have been reported from the deep sea sharks *Hexanchus nakamurai*, *Squalus megalops* and *S. melanurus* around New Caledonia at depths of between 300 and 900m (Trilles and Justine, 2004). A cymothoid isopod, *Elthusa parabothi* was described from *Parabothus kiensis* caught at around 400m off New Caledonia; no pathology was noted associated with the parasite (Trilles and Justine, 2004).

Limited specific studies have been conducted on the pathology associated with deep water parasitic copepods, with most reports being faunistic descriptions. Members of the families Sphyrriidae, and to a lesser extent Pennellidae, attach to their fish host by burrowing deep into the musculature. The pathology associated with penetration and attachment into the musculature of *Sebastes* spp. by *Sphyrion lumpi* is well

documented. Ulceration at the point of attachment is common (Gaevskaya and Kovaleva, 1984), with a connective tissue capsule surrounding the head of the parasite within the tissues. It is assumed that all members of the Sphyrriidae and Pennellidae elicit a similar host response with the possibility of secondary infections affecting the host through the open attachment point. The pennellids *Pseudolernaeopodina synaphobranchi* and *Lernaeopodina longibrachia* attach to the eyes of *Synaphobranchus kaupi* and *Hydrolagus affinis* respectively (Hogans, 1988a; Karlsbakk *et al.*, 2002). Whilst no pathology was reported in either of these reports, it is known that copepod infections of the eye can be detrimental to host survival (Benz *et al.*, 2002a; Borucinska *et al.*, 1998). However, in examining eyes of Greenland sharks infected with *Ommatokoita elongata*, (Borucinska *et al.*, 1998) concluded that whilst there was strong evidence of destruction of the eye leading to blindness, they were unable to unequivocally demonstrate a detrimental impact of the parasite on host survival possibly due to the host's habit of relying on olfactory rather than visual cues to find its prey. It is therefore possible that a similar process is occurring with other deep water fish affected by eye copepods. *Sarcotaces* spp. encyst in the musculature within a small sac like structure filled with an inky like substance that is derived from the haematophagous nature of the parasite (Bullock *et al.*, 1986). The presence of this inky black liquid gives rise to the common name for this parasite of "iodine worms". Whilst not particularly pathogenic to the host, the parasite can reduce marketability of the host if the sac is cut during processing as the fluid can taint the flesh.

The pennellid *Cardiodectes medusaeus*, whilst seen attached to the outside of lantern fish, actually penetrate through to the bulbus arteriosus of the heart (Perkins, 1983; Perkins, 1985). The parasite has a two host lifecycle, with juvenile, postembryonic stages occurring in the mantle cavity of pelagic gastropods (Perkins, 1983). Whilst the parasite castrates the host and is able to promote somatic growth of both male and female fish, there appears to be no relationship between host length and parasite numbers (Moser and Taylor, 1978). In addition, Moser and Taylor (1978) suggested that mortalities are directly attributable to presence of the parasite, which feeds on host erythrocytes (Perkins, 1985). On the other hand the pennellid *Sarcotretes scopeli* retards growth and gonadal maturation of its host *Benthoosema glaciale* (Gjøsaeter, 1971), whilst the cirriped *Anelasma*

*squalicola* retards gonadal maturation of *Etmopterus spinax* and, in older sharks can “exhaust the resources of the host” (Hickling, 1963). An unidentified isopod on the external surfaces of this small shark have been noted which apparently feeds on the blood of the host.

Table 1. List of genera of parasitic copepods reported from deep water fish.

Order	Family	Genus	Number of deep water species	Typical hosts	Geographical area	Reference	Depths
Siphonostomatoida	Sphyrriidae	<i>Lophoura</i>	15+	Macrouridae, Apogonidae, Synphobranchidae	Atlantic, Pacific	(Boxshall, 1989; Boxshall, 2000; Gómez <i>et al.</i> , 2009; Hogans and Dadswell, 1985)	600-2500m
		<i>Paeonocanthus</i>	2	<i>Bathylagus</i> spp.	Antarctic, North Atlantic	(Ho <i>et al.</i> , 2003; Hogans, 1986)	800-2700m
		<i>Periplexis</i>	1	Alepocephalidae	Indo-Pacific	(Boxshall, 2000)	900m
		<i>Sphyrion</i>	2	Macrouridae, <i>Sebastes</i> , Ophiidiids	Pacific, Atlantic	(Gaevskaya and Kovaleva, 1984)	100-500m
	Lernaeopodidae	<i>Brachiella</i>	1	Macrouridae	Pacific	(Ho, 1975)	1710-3330m
		<i>Clavella</i>	10+	Macrourids	North Atlantic, Antarctic, Japan	(Castro and Gonzalez, 2009; Ho, 1993)	-
		<i>Eubrachiella</i>	1	Nototheniidae	Antarctic	(Ho and Takeuchi, 1996)	100-820m
		<i>Lernaeopodina</i>	2	Holocephalans, <i>Centrophorus</i> ,	Atlantic	(Kabata, 2004; Karlsbakk <i>et al.</i> , 2002)	1300 -2100m
		<i>Parabrachiella</i>	1	<i>Sebastes</i>	Pacific, Atlantic	(Leaman and Kabata, 1987)	200-350m
		<i>Pseudolernaeopodina</i>	1	<i>Synphobranchus</i>	New Jersey, USA	(Hogans, 1988a)	1975m
	Pennellidae	<i>Cardiodectes</i>	1	Myctophidae	Pacific	(Boxshall, 2000; Moser and Taylor, 1978; Perkins, 1983)	1000m
		<i>Exopenna</i>	1	<i>Antimora</i>	France	(Boxshall, 1986)	2540m
		<i>Peniculus</i>	1	<i>Sebastes</i>	North east Pacific	(Kabata and Wilkes, 1977)	-
		<i>Sarcotretes</i>	2	Macrourids Myctophids	New Caledonia, Atlantic, Pacific	(Boxshall, 1989; Cherel and	770m

Order	Family	Genus	Number of deep water species	Typical hosts	Geographical area	Reference	Depths
				Hatchet fish, Melanocetidae, Bathylagidae		Boxshall, 2004; Hogans, 1988b)	
Siphonostomatoida	Hyponeoidea	<i>Greeniedeets</i>	1	<i>Centrophorus</i>	Madagascar	(Benz, 2006)	-
		<i>Hyponeo</i>	1	Paralepid	North Pacific	(Ho, 1987)	830m
		<i>Tautochondria</i>	1	<i>Anoplogaster</i>	Grand Banks, Nova Scotia	(Ho, 1987)	970-1300m
	Hatschekiidae	<i>Laminohatschekia</i>	1	Eels	New Caledonia	(Boxshall, 1989)	970m
	Archdactylinidae	<i>Archidactylina</i>	1	Hagfishes	Japan	(Izawa, 1996)	300-600m
	Caligidae	<i>Avitocaligus</i>	1	Trichiuridae	New Caledonia	(Boxshall and Justine, 2005)	150-400m
Cyclopoida	Chondracanthidae	<i>Chondracanthodes</i>	3	Macrourids	Atlantic and Pacific Ocean	(Ho, 1975; Ho, 1994; Østergaard, 2003; Østergaard and Boxshall, 2004)	1000-5440m
		<i>Lateracanthus</i>	2	Macrourids	Aleutian Deep, Chile	(Castro Romero, 2001)	1115-1150m
		<i>Jusheyhoea</i>	3	Macrourids	Japan, Hawaii, Chile	(Ho, 1994; Kabata, 1991; Salinas <i>et al.</i> , 2008)	540-700m
		<i>Chelonichondria</i>	1	Macrourids	Japan	(Ho, 1994)	1185m
		<i>Chondracanthus</i>	1	Macrourids	Japan, Atlantic, Australia	(Ho, 1994)	450m+
	Philichthyidae	<i>Sarcotaces</i>	2	Macrourids Morids	North Atlantic	(Bullock <i>et al.</i> , 1986) <i>et al</i>	400-2000m
	Lernaeosoleidae	<i>Bobkabata</i>	1	Sculpins	Northwest Atlantic, Western North Pacific	(Benz <i>et al.</i> , 2002b; Benz and Braswell, 1998; Hogans and Benz, 1990)	1400m

### 3. Parasites as tags

The use of parasites as biological tags has a long and varied history. However, in part due to the somewhat simplistic statistical approaches used by previous researchers, they have been dismissed by workers in other fields as lacking suitable rigour. However, recent advances in statistical approaches and a greater understanding of the underlying reasons for variability of parasite faunas between stocks has led to an increased revival in their application (Ayvazian *et al.*, 2004; Brickle and MacKenzie, 2007; Lester and MacKenzie, 2009; MacKenzie and Abaunza, 1998; Marcogliese *et al.*, 2003; Pawson and Jennings, 1996; Perdiguero-Alonso *et al.*, 2008; Power *et al.*, 2005; Santos *et al.*, 2009).

Parasites have been used as biological indicators of population biology, migration, diet, phylogeny, recruitment, origin of fish products and pollution (including as bioaccumulators of heavy metals) (Abaunza *et al.*, 2008; Bakay and Melnikov, 2002; Baker *et al.*, 2007; Brickle and MacKenzie, 2007; Durieux *et al.*, 2007; Durieux *et al.*, 2010; Ferrer-Castelló *et al.*, 2007; Grutter, 1998; Lester and MacKenzie, 2009; MacKenzie, 2002; MacKenzie and Abaunza, 1998; MacKenzie and Longshaw, 1995; Marcogliese *et al.*, 2003; Moles *et al.*, 1998; Oliva, 2001; Oliva *et al.*, 2008; Power *et al.*, 2005; Sures *et al.*, 1997a; Sures *et al.*, 1997b; Sures *et al.*, 1999; Sures, 2001; Sures and Reimann, 2003; Walker and Myers, 1992; Yanulov, 1974).

The basic premise of the use of parasites as tags is that fish can only become infected with a parasite when they come within the area which is suitable for transmission of the parasite. Thus if a fish is found infected with a particular parasite species outside of this endemic area, it follows that the host must have been inside this endemic region at some point in its life-history. Coupled with information on the parasite longevity and to a lesser extent, lifecycle data, it is possible to infer the maximum length of time since the host came in contact with the parasite in question. Clearly the more parasites from different endemic areas examined the greater the resolution of information. The different lifecycle strategies employed by parasites impact on the utility of tags, with those having direct or simple lifecycles being affected more by environmental conditions whilst those parasites requiring two or more host lifecycles have a requirement for all hosts to be present in order for the lifecycle to be completed. MacKenzie and Abaunza (1998) considers that parasite

tags should be seen as complimentary to other approaches for ascertaining biological data such as genetics, mechanical tags and other biological characteristics. Clearly this integrated approach will provide a more powerful data set to understand the whole biology and ecology of the host compared with singular approaches. Biological tags have a number of advantages over mechanical tags including being more appropriate for deep water fish and delicate species that may be damaged or killed by the action of tagging or for species where it is impossible to attach tags for whatever reason. The approach is considered less expensive as samples can be obtained from routine sampling programmes without the need to rely on cruises specifically designed for tagging although provenance of the samples collected needs to be ensured. In addition, the use of biological tags eliminates any doubts surrounding the possible abnormal behaviour of artificially tagged hosts and limits the low return experienced by mechanically tagged fish. Collection of other biological data (including gut contents) at the same time provides a robust data set for analysis. Recent novel approaches to discriminating stocks through the use of parasites include random forests; a statistical modelling approach that is essentially an ensemble of learning techniques where individual decisions of a large set of random classifiers are combined by majority voting in order to obtain predictions that are more accurate than any individual classifier such as linear discriminant analysis or artificial neural networks (Perdiguero-Alonso *et al.*, 2008).

### *3.1 Applications in deep sea fish*

Several studies have been conducted explicitly on the use of parasites as biological tags for deep sea fish. In addition, studies have been conducted on parasite faunas of deep sea fish from different areas but no implications have been made by those authors regarding the utility of the parasite faunas as tags. One of the more widely studied group of deep water fish with regards tags are grenadiers (*Coryphaenoides* and *Macrourus* spp.). Clear differences in the parasite faunas and in prevalences were noted by (Szuks, 1980; Walter *et al.*, 2002; Zubchenko, 1985) for these hosts, strongly supporting the value in using parasites as biological tags for stock structure. Several studies of the parasite fauna of the Patagonian toothfish have consistently shown that they possess different parasite faunas depending on depth of capture and geographical locality with strong evidence that the differences observed are stable and thus parasite faunas can be useful tags for stock structure (Brickle *et al.*,

2006; Oliva *et al.*, 2008). Other studies involving the use of parasites as biological tags includes those of the redfish (*Sebastes* spp.). For many years the copepod parasite *Sphyrion* sp. has successfully been used as a stock discrimination tag. Differences in parasite faunas of *S. mentella* were used to suggest that different, reproductively isolated stocks of this host exist across its range (Bakaj, 1993; Bakay, 1988; Bakay, 2001; Bakay and Mel'Nikov, 2008; Bakay and Melnikov, 2002; Melnikov and Bakay, 2009). Similar results were obtained by Moran *et al.* (1996) for redfish collected off Canada.

There are very clear examples in the literature where the application of parasites as biological tags for stock structure in deep sea fish has been successful. An initial assessment of parasites that may prove useful include protistans, monogeneans and copepods. Thus, studies should be directed towards these major groups in the first instance.

#### **4. Contaminants**

Concern on the effect of anthropogenic contaminants on the deep sea fauna has only recently resulted in studies to examine contaminant burdens in deep sea fish species. Investigations in the Atlantic Ocean are few and have been restricted to organic compounds (Barber & Warlen, 1979; Kramer *et al.*, 1984; Froescheis *et al.*, 2000; Webster *et al.*, 2009). Increasingly it appears that deep water environments can act as a sink for contaminants and that bioaccumulation in the resident fauna, particularly fish, is a significant issue for those species in particular that may be suitable for human consumption. Organic pollutants in benthic fish species may be between 10 and 17 times higher than that measured in surface species (Looser *et al.*, 2000). Studies on polychlorobiphenyls (PCBs) and pesticides have been undertaken in black scabbardfish (*Aphanopus carbo*), orange roughy (*Hoplostethus atlanticus*), roundnose grenadier (*C. rupestris*) and *Bathysaurus ferox* from a number of locations in the North eastern Atlantic (Mormede & Davies, 2003). For several of the species investigated by these authors, contaminant levels were elevated in males compared to females. This was thought to be due to elimination in females through egg production. Highest levels of contaminants were found in the deepest dwelling species, *B. ferox* with concentrations up to 10 times higher than that recorded in other species. A more recent study by Webster *et al.* (2009) examining

chlorobiphenyls (CBs) in fish collected from the Rockall Trough off the west of Scotland (North east Atlantic Ocean) showed that for some fish species levels in the liver were above OSPAR Background Assessment Concentrations (BAC). However, analysis of the data using published models showed that consumption of fish muscle is unlikely to pose a risk to human health. Contamination with PCBs and organochlorine pesticides in deep-sea fish from the Mediterranean Sea has also been identified (Storelli *et al.*, 2007, 2009). The authors draw attention to the potential adverse health effects on the fish and for the need to undertake further assessments to allow effective management and long-term conservation of the ecosystem in the region. Few investigations into heavy metal contamination have been undertaken (Fowler, 1990). A number of studies have been undertaken in the Eastern Atlantic in Portuguese waters. Afonso *et al.* (2007) and Costa *et al.* (2009) showed that levels of mercury, cadmium and lead concentrations in black scabbardfish were highest in the liver for mercury and cadmium and in the gonad for lead. Fish captured from around Madeira were found to contain significantly higher levels of metals than in fish from areas off the mainland and the Azores. It was suggested by Afonso *et al.* (2007) that moderate consumption of black scabbardfish muscle from these areas does not pose a risk to human health. Analysis of other deep water species in Portuguese waters confirms the view that the flesh should only be consumed sparingly (Afonso *et al.*, 2008).

## **5. Summary, conclusions and recommendations**

This brief review has indicated that there is a paucity of information on the health status of deep sea fish species. Most studies to date have been of the metazoan parasite fauna of adult fish and most of these have been studies have involved taxonomic studies. A clear gap in knowledge is of the presence and effect of viral, bacteriological, fungal and protistan pathogens in deep sea fish. This is a significant area that requires study since these pathogens are normally associated with acute infections and frequently lead to physiological impairment, debilitation and death. Without collecting baseline information it is impossible to estimate their effect on individuals and populations. A key driver will be to improve understanding of pathogenicity of the parasites detected, to be able to determine their effects on

individuals and to model their effects on recruitment to adult populations and population structure. There is growing information from freshwater environments that chronic parasitism in juvenile life stages does have a significant effect at the population level (Longshaw *et al.*, 2010). It is likely that deep sea fish species will also be exposed to similar pressures. However, the ability to measure impacts in these populations is dependant on;

- 1) improving knowledge on the life history patterns of target species;
- 2) obtaining information on the pathogens affecting individuals at various stages in their growth;
- 3) establishing trend information on disease presence for key species

***Recommendation 1:*** *It is recommended that baseline surveys be undertaken to establish the effects of prokaryotic (viruses and bacteria) and protistan pathogens on deep-sea fish species of potential commercial interest.*

It is clearly indicated in the scientific literature that parasites can be of significant use as stock indicators in exploited stocks in shallow seas. A few investigations have been undertaken for the use of parasites for stock discrimination based on ecological stocks, which may be more useful for management purposes than genetic stock discrimination, particularly for species with very wide or global distribution. There is excellent potential for developing this ability based on parasite fauna, provided material can be obtained. This will probably not require extensive annual monitoring since available evidence from previous investigations in shallow water stocks suggests that patterns are relatively stable over several years extending to decades and possibly further.

***Recommendation 2:*** *It is recommended that parasitological surveys be undertaken for the main species of interest and over wide geographic regions. This should be co-ordinated between EU member states and involve other countries as appropriate.*

There remains a general lack of information on contaminant burdens over much of the globe with some areas more extensively studied. Although contaminant burdens are generally not high enough for human health concern, it has been established that the deep sea fauna has higher burdens of organochlorine compounds than in

'surface' living species (Froeschecis *et al.*, 2000). An important factor of specific relevance to deep sea fish species is their longevity. In surface fish, macroscopic tumour formation occurs from approximately two years of age and appears to have a detrimental impact on survival (Myers *et al.*, 2008). Whether deep sea fish exposed to contaminants are susceptible to tumour formation is currently unknown but bearing in mind the fact that most species (fish or otherwise) are susceptible to one or more forms of cancer suggests that deep sea fish are no exception, particularly taking into account their longevity. Heavy metal burdens can be above EU limits and vary considerably between species. There are currently no data on toxicopathic effects of these substances in deep sea fish. Fish health monitoring in surface dwelling fish species is well established internationally via the Oslo and Paris Convention (OSPAR) and includes quality assured (via BEQUALM programme) assessment of externally visible disease conditions as well as the presence of liver nodules (organic contaminant induced tumours) and microscopic histological lesions. Taking into account the contaminant levels detected in deep sea fish and their longevity, the presence of toxicopathic effects, particularly in the liver could be expected.

***Recommendation 3:*** *It recommended that baseline information on the normal structure, histology and histopathological lesions (particularly those in the liver and hepatobiliary systems that are likely to be attributable to contaminant exposure) be established for benthic species with the aim to inform the development of a contaminant effects monitoring programme for deep sea fish.*

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